MR-based eddy current probe design for hidden defects

M. Pelkner\textsuperscript{a}, Th. Erthner\textsuperscript{a}, V. Reimund\textsuperscript{a}, M. Kreutzbruck\textsuperscript{a}, N. Sergeeva-Chollet\textsuperscript{b}

\textsuperscript{a}BAM Federal Institute for Materials Research and Testing, Unter den Eichen 87, 12205 Berlin, Germany
\textsuperscript{b}CEA LIST, 91191 Gif-sur-Yvette, France

Abstract
We present a simulation study which pursues the objective to find probe geometries for a MR-based eddy current (EC) probe (MR magneto resistance, e.g., GMR giant magneto resistance, TMR tunnel magneto resistance). MR sensor technology exhibits two significant advantages compared with conventional coil systems. First, MR sensors are relatively frequency-independent within common EC-frequency ranges which enable us to operate them in hidden defects testing problems. Secondly, MR technology is well suited for miniaturization helping us to design small elements in the order of below 100 µm. In this paper simulation and experimental results obtained with the probes for low frequency application, i.e. for hidden defects detection are discussed.

Our simulations are based on two different approaches for a better validation, a commercial finite element method software (Opera, Vectorfields) and the semi-analytical software CIVA. We investigated both coil arrangement in order to excite sufficient high eddy currents inside the test samples and position of MR-elements at the array chip. In doing so the MR sensors were positioned that they are not exposed to excitation fields. In addition, different coil geometries, in particular coil length, e.g. $l = 20$ mm, were analyzed in order to generate a consistent eddy current distribution beneath an array of up to 32 MR-elements. To prove obtained probe principles we built GMR-EC-probes. The first test measurements are in good agreement with the simulations performed by BAM and CEA. On basis of our findings the IMAGIC consortium developed new MR-EC-probes using integrated ASIC technology.

Keywords: magneto resistance (MR), eddy current (EC), simulation

1. Introduction

Conventional eddy current (EC) probes are suited for the detection of surface breaking defects in conductive materials [1-3]. Defects in the sub-mm-range can be detected with a good SNR (signal-to-noise ratio). Conventional EC probes employ coils as emitter and receiver leading to some drawbacks when it comes to the detection of hidden defects. Using coils as receivers leads to a strong dependence of the testing frequency because of Faraday’s law. High frequencies generate high currents inside material under test and especially at the surface leading to a high response signal in the presence of surface cracks (see Figure 1).

Figure 1: Principles of eddy currents in terms of surface and buried defects due to skin depth.

To detect defects under the surface (see Figure 1) the emitter frequency has to be reduced to induce eddy currents deeper inside the material because of skin effect. However, the detected signal will be reduced by decreasing frequency and make a detection of buried flaws hardly
achievable using coils. Besides these limits, coils systems offer also a low spatial resolution caused by the dimension of the receiver coils which in case of buried flaws can be seen as negligible.

To overcome these drawbacks we performed an optimization for an appropriate eddy current probe for hidden defects using coils for excitation and MR elements (magneto resistance) as receiver [4,5]. GMR and TMR sensors (giant magneto resistance, tunnel magneto resistance) provide a high field sensitivity, they are cheap, and can be built in small dimension increasing spatial resolution without losing sensitivity compared to coils. The main advantage using MR elements (MR refers in the following to both GMR and TMR) is their almost frequency independence which make them ideally suited for low frequency applications.

In this paper we present this design study of a MR-EC-probe for buried flaws leading to probe geometries which are eligible for hidden defect detection. To prove the principles we built in a first step probes referring to the optimization to investigate their applicable employment. Therefore, we measured the response from buried flaws in several mock-ups and discuss these results in order to build appropriate ASIC-MR-EC-probes for hidden defect detection.

2. Simulation

The optimization study for a MR-EC-probe for buried flaws has to comprise several requirements: generation of high eddy currents deep inside the material, appropriate geometry of the excitation coils, and capable position of MR elements inside the probe. For our simulations referring to the above mentioned demands we used two different tools: the eddy current tool of the semi-analytical software CIVA from CEA LIST [6], a powerful and fast software for the calculation of eddy currents and magnetic fields, and the commercial FEM (finite element method) software Opera from Vectorfields, which also calculates eddy currents in ferromagnetic materials. FEM tools calculate the field distribution iteratively using, in our case, tetrahedral elements.

![Figure 2: Left: FEM-simulation of a double coil design and the expected eddy current distribution inside the material under test. The diagram present the current density as function of the depth z for 7 frequencies. Right: Detail of the double coils. Sensor elements are positioned between the coils.](image-url)
In Figure 2 we show a double coil planar aligned to the surface under test for excitation of eddy currents. Also, single coils in different alignments were simulated. However, for buried flaws application these alignments were rejected. Below the left false rendering plot which pictures the eddy current field distribution inside the material we show a diagram depicting the current density of the black line in the false rendering plots for several excitation frequencies \(f = 100 \text{ – } 8000 \text{ Hz}\). Increasing depth leads to a decreasing current density. Further, higher frequencies will induce higher eddy currents at the surface. Inside the material lower frequencies in the order of 100 Hz generate higher currents due to skin effect. On the right of Figure 2 the double coil is shown in more detail. The considered position of MR-elements are marked with the black line.

![Figure 2: Double coil planar aligned to the surface under test for excitation of eddy currents.](image)

**Figure 3:** CIVA: Expected MR-signal for a buried defect.

Besides considerations of eddy currents deep inside the material, the coupling between sensor element and excitation field, and expected eddy current signals are important criterions for an appropriate probe design and the choice of sensor elements and their sensitivity direction. Figure 3 shows a simulated defect signal (normal field component, ligament 5 mm, Aluminum, coil geometry (see Figure 4): width \(w = 12 \text{ mm}\), length \(L = 20 \text{ mm}\), 1 turn, \(\text{NI} = 1\text{A}\), \(f = 400 \text{ Hz}\)) using a double-coil excitation. Simulation (CIVA) for tangential and normal field components show similar results in case of signal amplitude (155 nT and 152 nT, respectively). However, for measuring tangential field values there is a strong coupling between sensor and excitation field (288 nT). In case of normal field detection, no coupling occurs for sensor elements exactly in the centre between the two coils (see Figure 2).
Due to superposition of the generated magnetic fields and, therefore, higher eddy currents deep inside the material the double coil configuration is suited for the detection of buried flaws. In Figure 4 the parameters characterizing the probe are shown. The gap $d$ characterizes the distance between the two coils. Here, higher values lead to stronger eddy currents deep inside the material (see Figure 5). The second parameter characterizing the coils is the width $w$. Higher values for $w$ increase the current density inside the material (Figure 6). The length $l$ of the coils was also simulated (not shown) and should be longer than the scanning length of a GMR array onboard of the PCB. This is important to generate nearly the same eddy current distribution beneath each MR element.

Figure 4: Geometrical parameters describing the double coil arrangement.

Figure 5: Simulation FEM (Opera) for the current density $j_0$ inside the material as function of the depth $z$ for different gaps $d$ at a frequency of 100 Hz.

Figure 6: Comparison of (a) FEM and (b) CIVA. Current density $j_0$ for a frequency of 100 Hz for 5 different gaps between two excitation coils of a double coil configuration as function of the depth $z$. 
Also, we simulated the frequency dependence for several hidden defects with different ligaments (distance tip of defect - surface). Table 1 summarizes the simulation results for the normal field component (CIVA) and is similar to the current density diagram in Figure 2.

Table 1: Excitation frequencies and detect field amplitude for three buried defects.

<table>
<thead>
<tr>
<th>Ligament (mm)</th>
<th>Frequency (Hz)</th>
<th>Amplitude (nT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 mm</td>
<td>620</td>
<td>136</td>
</tr>
<tr>
<td></td>
<td>520</td>
<td>146</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>153</td>
</tr>
<tr>
<td>9 mm</td>
<td>400</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>17.7</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>17</td>
</tr>
<tr>
<td>16 mm</td>
<td>160</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>1.315</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Further simulations in case of frequency dependence for different coil geometries, evaluation of the current density in different depth, etc. yield to similar results. For the IMAGIC-consortiums these simulations were done to define an appropriate probe where an ASIC, GMR/TMR-elements and further electronics are assembled on one PCB. Here, also geometry aspects have to be considered since the available space is limited. For an eddy current probe for buried flaw detection we propose a double coil arrangement with dimensions of $w = 12$ mm, $d = 4$ mm, $l = 20$ mm.

3. Experiment

![Figure 6: Scheme of the double coil probe using a GMR sensor as receiver.](image)

A scheme of the probe and its geometrical parameters used for evaluation of the simulation is shown in Figure 6. The coils have an area of $l \times w = 20 \times 16$ mm². The distance between the two coils is $d = 6$ mm. Each coil has 40 windings. For the excitation we applied a current of $I_{AC} = 200$ mA. The GMR sensor (GF790b, Sensitec GmbH, Germany) is placed in the centre of the probe between the two coils to such an extent to avoid detection of background fields of the excitation coils (pictured by the green line in Figure 6).
The applied current was generated by a commercial EC-system (ELOTEST B1-V4, Rohmann GmbH). The GMR sensor signals were also recorded by this system. Between sensor and EC-system we placed an amplifier. Here, the gain factor was 40 dB during measurement. The sensor itself has a sensitivity of 40V/T.

Experiments were carried out for a plate made out of Aluminium. In this plate which is 10 mm thick were introduced 10 boreholes of different depth (see scheme in Figure 7). The boreholes have a diameter of 3.3 ± 0.3 mm. The depth varies from 1.12 mm up to 9.7 mm leading to ligaments from 8.88 mm down to 0.3 mm. The red box defines the scanned area of the plate. The scans were performed for hidden defects.

Figure 7: Aluminium sample with boreholes of different depth. Thickness of the plate is 10 mm leading to ligaments shown right of the scheme of the plate. The red box depicts the scanning area.

Experiments were carried out for a plate made out of Aluminium. In this plate which is 10 mm thick were introduced 10 boreholes of different depth (see scheme in Figure 7). The boreholes have a diameter of 3.3 ± 0.3 mm. The depth varies from 1.12 mm up to 9.7 mm leading to ligaments from 8.88 mm down to 0.3 mm. The red box defines the scanned area of the plate. The scans were performed for hidden defects.

Figure 8: (a) CSCAN of the plate (hidden boreholes). (b) Line scan for the borehole with the smallest ligament of 0.3 mm. The red circles mark the extreme values of the GMR signal for the defect signals.

Figure 8 (a) shows a CSCAN of the Aluminium mock-up. The excitation frequency was 500 Hz. Here, defects with ligament up to 5.72 mm could be resolved with SNR better than 6 dB. The red line indicates the line scan for the defect with a ligament of 0.33 mm shown in
Figure 8 (b). Here, the red circles mark the extreme values of the measured GMR-EC-signal which were used to calculate SNR values in the following.

Figure 9: SNR as function of the frequency for three different ligaments.

In Figure 9 we present a frequency-dependent measurement of boreholes with a ligament of 0.33 mm (black), 2.72 mm (red) and 4.73 mm (green). Diagrammed is SNR as function of excitation frequency $f$. The curves of ligament 1 and 4 refer to the left y-axis, the green curve refer to the right y-axis indicated by the green colour.

For defect 1 and 4 SNR increases for increasing frequency. Here, the superposition of the magnetic fields and, therefore, the eddy currents inside the material increase at defect position. The maximum in SNR is not reached for the chosen frequency range. Further increasing the frequency will lead to a maximum and then a decreasing of SNR since the skin effect will become stronger. In case of defect no. 6 a maximum in SNR is reached for $f = 600$ Hz. For higher frequencies the skin depth decreases leading to a worse superposition of magnetic fields and, therefore, eddy currents at the defect position of no. 6. These results are confirmed for another test sample made out of ferromagnetic material. Here, the skin depth is further reduced because of the additional magnetic permeability.

4. Conclusion

Using MR sensors as receivers in an EC-testing system is a suitable way for the detection of buried flaws due to low emitter frequencies. For this purpose we designed a double coil arrangement based on our simulations using FEM-software Opera and semi-analytical CIVA, respectively.

A prototype was built to test the simulated principles of the double coil configuration. Our results are the basis to develop new probes which combine MR sensor technology and ASIC integration in one probe.

Acknowledgement

This work is supported by the European project IMAGIC FP7 288381.
References


