EDDY CURRENT TESTING WITH HIGH-SPATIAL RESOLUTION PROBES USING MR ARRAYS AS RECEIVER

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Abstract. Magneto-resistive (MR) sensor arrays are suited for high resolution eddy current testing (ET) of aerospace components due to two significant advantages compared to conventional coil systems. First, to obtain high spatial resolution they can be manufactured down to the µm-regime without losing their outstanding field sensitivity. Secondly, MR technology has a relatively frequency-independent sensitivity in the range of common ET-frequencies thus providing a benefit for low frequency applications.

This paper presents measurements using MR array probes consisting of 32 TMR-elements (tunnel magneto resistance), an ASIC, and subsequent readout components. A source for generating the eddy currents inside the material under test is also implemented onboard of the PCB. These probes were developed in the IMAGIC-project* for detection and imaging of surface breaking defects.

The performance of the new sensor system has been investigated for several mock-ups, Aluminum and Titanium plate specimens having small adjacent boreholes with diameter of 0.44 mm and micro notches in the µm-range, respectively. To compare our results we used conventional eddy current probes. The MR sensor elements have a length of around 60 µm leading to a nearly “point like” measurement. Neighbouring boreholes (depth 0.25 mm) with a separation of 0.6 mm between their centres could be resolved with a good SNR, and more important, the boreholes could be confidently distinguished using the TMR-probes. In case of conventional probes a reliable separation was not possible. In this paper we present the MR-ET-probes of the IMAGIC consortium and a comparison with conventional techniques.

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Introduction

Aircraft components are exposed to harsh external conditions like large temperature differences, potential impact events and strong cyclic load profiles. This is why according to strict safety regulation aircraft components have to be inspected regularly during maintenance cycles using non-destructive testing (NDT) methods. Eddy current testing (ET) is an often used NDT method in aviation industry [1-7] since many components are made out of conductive materials like Aluminum and Titanium. ET is suited for determination of the degree of material thinning, i.e. corrosion [1], and for detection of surface breaking defects [2].

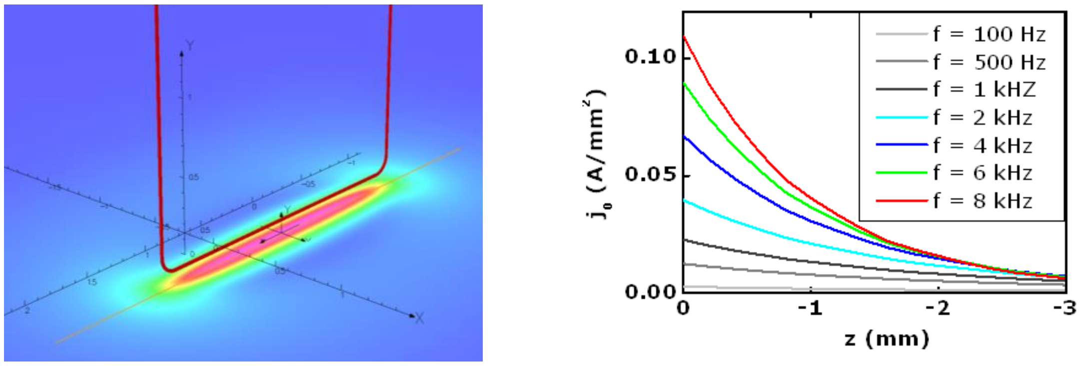
Conventional ET sensors consist of coils as receivers leading to a frequency dependence of the detected eddy current signals. In case of high spatial resolution or buried flaws it can be advantageous to use other magnetic field sensors. The magnetic field sensor comprising the best magnetic field sensitivity down to pT/√Hz for low frequencies is a SQUID magnetometer. It is suitable for the detection of buried flaws, e.g., 40 mm deep defects inside Aluminum plates [3]. To increase spatial resolution magneto resistive (MR) sensors can be used for NDT applications. Here, mainly GMR (giant magneto resistance) [4,8] and TMR (tunnel magneto resistance) [5] probes are suitable. These sensors combine an extraordinary field sensitivity with an excellent spatial resolution due to their capability of miniaturization. In addition, they can be purchased keeping down costs and require a low power consumption. Furthermore, arrays containing 32 and more elements can be used in order to decrease measuring time. Another advantage is their flat frequency response for a large frequency range especially for low frequencies compared to conventional coil systems. Thus, these sensors are also suitable for detection of buried flaws [9,10].

This paper presents measurements using TMR ET-probes for small surface breaking defects [11] in the sub-mm regime. Additional ASICs (application-specified integrated circuit) [12] for processing the sensor signals of 32 MR-elements are on board of the PCBs. These probes were developed in the IMAGIC-project ("Integrated Magnetic imagery based on spIntronics Components", 2011 – 2014, EU-project reference: 288381). We investigated two different materials used for aerospace components – Al- and Ti-samples. In case of Aluminum our focus lays on the separation of two defects. Titanium, a material with lower conductivity, is suitable for tests concerning the detection of defects in the µm-range. In order to gain spatial resolution also on the excitation side we excited the eddy currents using only one wire. Finally, our findings were compared with results obtained by conventional ET-technique.

MR-ASIC probe

The IMAGIC-consortium developed two different types of GMR-/TMR-based ET-probes for buried flaws and for small surface breaking cracks [9-13], respectively. The latter requires small MR elements. For this purpose, GMR/TMR sensor arrays were developed with sizes in the order of 60 µm which serve as receivers.

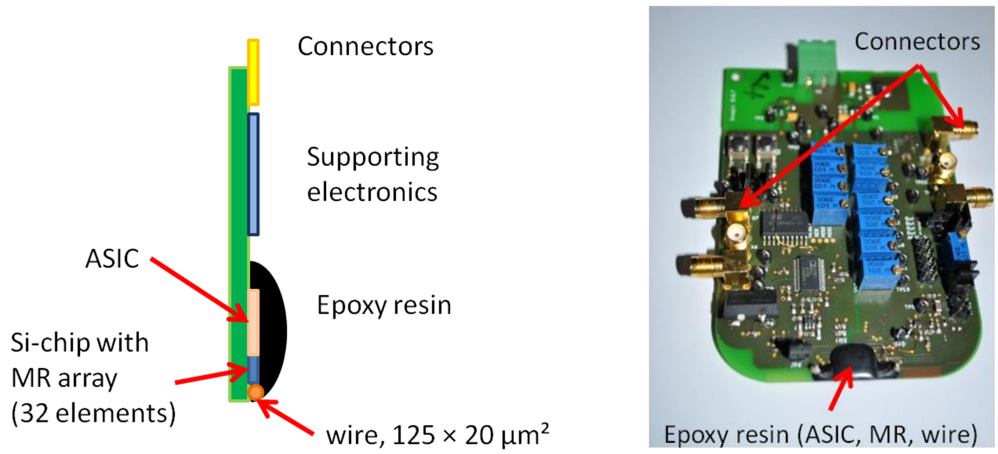
We investigated several arrangements of excitation coils [9,10] and simulated their influence on the eddy current distribution inside a certain material using two different simulation tools – commercial FEM-software Opera (Vector-fields) and semi-analytical software CIVA developed by CEA. Fig. 1 (a) shows as an example the arrangement of a one-wire excitation. Beneath the wire (red line) the excited eddy currents are illustrated as false rendering plot. Fig. 1 (b) represents the eddy currents j_0 as function of the depth z exactly in the centre beneath the wire for 7 excitation frequencies. Increasing frequency leads to higher eddy currents at the surface. Since, this arrangement is considered for surface breaking defects high excitation frequencies up to MHz are advantageous.



(a) (b)

Fig. 1. (a) Illustration of FEM-simulated eddy current distribution at the surface excited by one wire. (b) Eddy currents j_0 as function of the depth z beneath the wire for different excitation frequencies.

Using one wire has several advantages. First of all, the wire can be placed at the same PCB for MR arrays (GMR or TMR) and ASIC (shown in the scheme of Fig. 2 (a)). Since, it has to be near the surface in order to reduce loss of excitation inside the material under test it is positioned at the edge of the PCB. Also, the arrays sensitive to the normal field component has to be near the surface. Therefore, they are positioned directly behind the wire. Wire, sensor arrays and ASIC are protected by an epoxy resin. The second advantage of this arrangement is that at sensor array position the background field by the wire is zero for the normal field component leading to a better processing of the signals. Fig. 2 (b) shows the PCB (developed and assembled by *Sensitec GmbH (Lahnau, Germany)*, see also [14]). At the bottom edge in the middle is the epoxy resin. The TMR arrays [11] and the ASIC are connected beneath the resin. The ASIC process the sensor signals coming from the array. This includes among other things amplifying and multiplexing [12]. For the first probes additional downstream electronics are onboard the PCB to adjust sensor signals and to setup gain for amplifying.



(a) (b)

Fig. 2. (a) Scheme of the PCB (not to scale) with excitation wire, MR array (GMR or TMR), and ASIC protected by an epoxy resin. In addition supporting electronics and connectors are placed on the PCB. (b) Photo of the IMAGIC TMR probe.

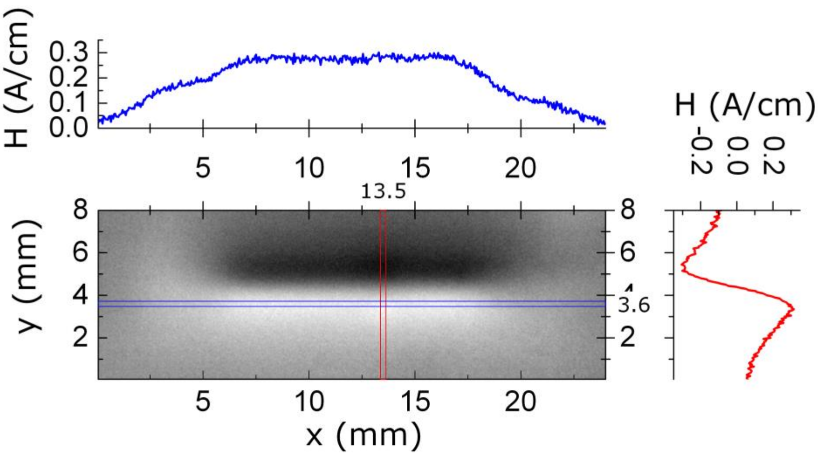


Fig. 3. Grey-scaled representation of the magnetic field distribution excited by a wire of a MR surface probe for an excitation current of I = 400 mA. The field strength was measured using a Hall-sensor. Line strips of the field distribution parallel (blue stripe and curve) and perpendicular (red stripe and curve) to the wire. The maximum and minimum magnetic field excited by the wire in a distance of 500 µm is ±0.35 A/cm.

Fig. 3 presents the magnetic field distribution of the wire. The wire at the edge of the PCB has a length of 10 mm, and a cross section of ca. 125 × 20 µm². The magnetic field strength was measured using a Hall-probe. For an applied current of 400 mA the maximum and minimum magnetic field is ± 0.35 A/cm measured at a distance of 500 µm. Furthermore, the magnetic field distribution is homogenous over the length of the wire leading to a constant eddy current distribution inside the material. This is important for a reliable testing of surface breaking defects.

Results

For first tests of the new probes we investigated an Aluminum test sample with small boreholes in a row (see scheme Fig. 4). The diameters of the holes are 0.44 – 0.45 mm. This sample is suited for testing spatial resolution since the distance between the boreholes decreases from 2 mm down to 0.6 mm. The geometrical sizes of the boreholes are listed in table 1. All specifications are in mm.

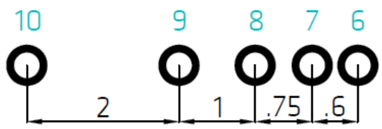


Fig. 4. Scheme of the boreholes no. 6 – 10 of Aluminum test sample Al-FN-22. The unit of the lengths is mm.

Table 1. Diameter and depth of boreholes of test sample Al-FN-22 in mm.

No.	Diameter (mm)	Depth (mm)
6	∅ 0.440	0.25
7	∅ 0.450	0.256
8	∅ 0.445	0.253
9	∅ 0.440	0.254
10	∅ 0.440	0.254

In the following data using eddy current systems based on coils as receivers are compared with MR-based probes. For this purpose we deployed the differential probe "KDS 2-2" from *Rohmann GmbH* (*Germany*), a non-commercial absolute probe ("A05", *BAM*) with a core diameter of 0.5 mm, a high-resolution, non-commercial probe ("AN05", *BAM*; diameter 0.5 mm; [1]), and the TMR ASIC probe. The excitation frequency and the current were 310 kHz and 200 mA, respectively. In case of the TMR-probe the chosen parameters were f = 1.3 MHz and I_{wire} = 100 mA. The results are shown in Fig. 5 as grey-scaled plot on the left and line scan on the right (position indicated by the coloured stripe in the grey-scaled plots). The ET-equipment used for data acquisition was a "B1 V4" (*Rohmann GmbH*) except for the TMR-probe. Here, we used a NI-system for recording the data. Displayed are the results of the Y-channel with an additional phase rotation (common procedure in ET).

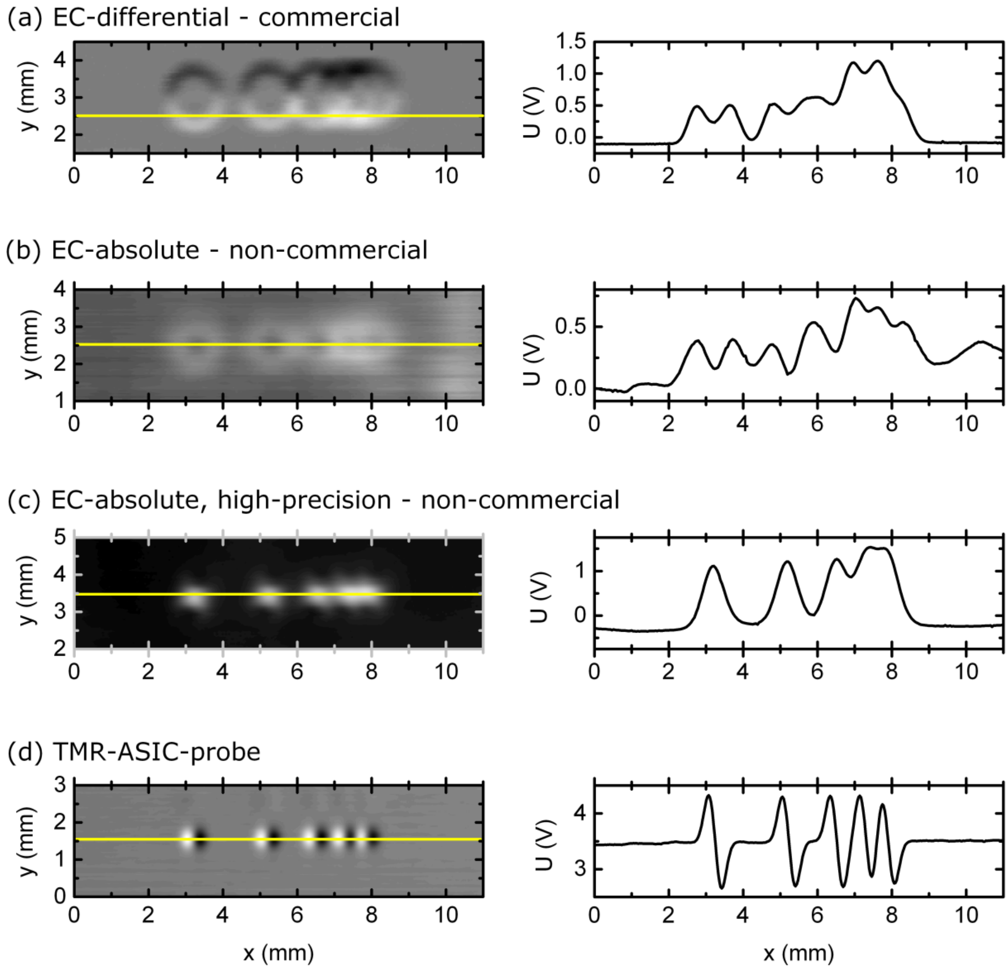


Fig. 5. ET-data of Aluminum-sample Al-FN-22 for different probes ((a) differential probe "KDS 2-2" of *Rohmann GmbH*, (b) absolute probe BAM-made "A05", (c) absolute, high-precision probe BAM-made "AN05", and (d) TMR-ASIC-probe of the IMAGIC consortium for surface breaking defects) as grey-scaled plots on the left and as line cut across defect signals on the right.

In case of conventional eddy current technique – differential (Fig. 5 (a)) and absolute ET-probes (Fig. 5 (b)) – a separation of defect no. 6 and 7 is not possible due to the diameter of the coils. Also, defect 7 and 8 can hardly be distinguished. To compare the signal amplitude of all probes we determined the SNR (signal-to-noise-ratio) of defect no. 10. Here, we can emanate from no overlapping of eddy current signals due to the distance of 2 mm to the neighbouring borehole no. 9 (see Fig. 4). Using a gain of 45 dB we obtained for the differential and the absolute probe SNR(KDS 2-2) = 25.1 dB and SNR(A05) = 5.4 dB, respectively.

A better distinction can be reached using the BAM-made high-precision probe

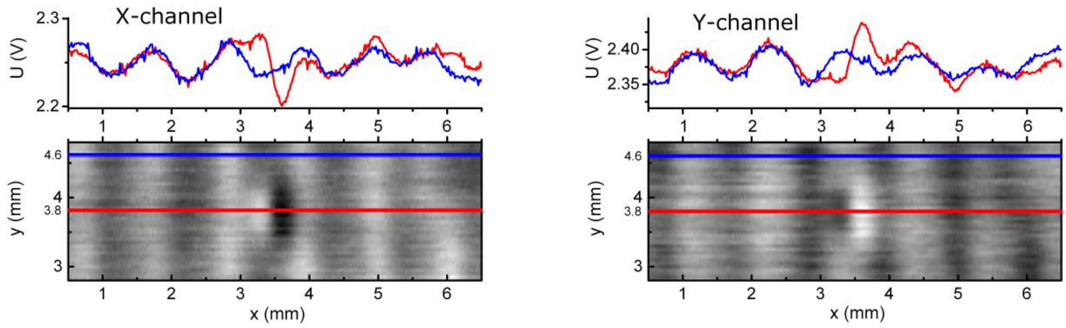
AN05 (Fig. 5 (c); see also ref. [1]). The line scan indicates a separation of defect 6 and 7 (red circle in Fig. 5 (c)), however, a full distinction is achieved for no. 7 and 8 which are 0.75 mm apart. For defect 10 the SNR-value is 26.2 dB.

Fig. 5 (d) presents the result of the TMR-probe. The gain factor used to pre-amplify the signals was 40 dB. Due to the small sensing elements and the small distance between sensing element and surface under test we obtained a better spatial resolution compared with ET-probes based on coil-systems. The line scan in Fig. 5 (d) shows that defect no. 6 and 7 with a distance of 0.6 mm could be resolved. The SNR of defect no. 10 is 34.1 dB.

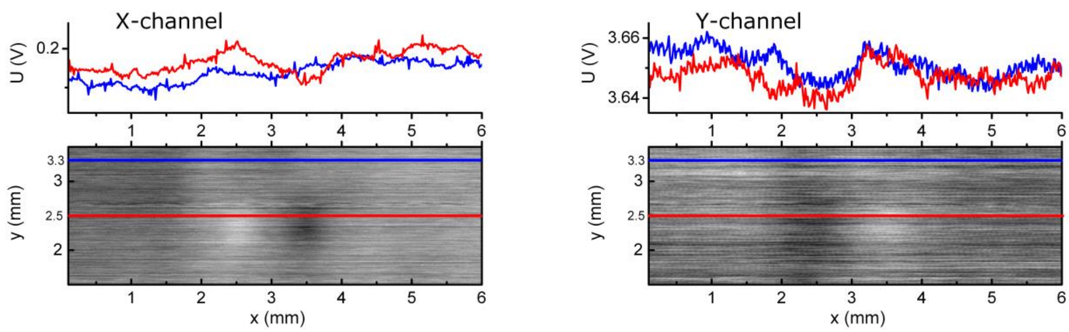
Another material often used in aerospace industry is Titanium (Ti). Since, the conductivity of Ti (σ = 0.60 MS/m) is low compared to Aluminum (σ = 20.5 MS/m) the expected ET-signals will be small. This makes it harder to detect small defects having sizes in the µm-regime. The conductivity of both materials was determined using the conductivity meter SIGMATEST 2.069 (*FOERSTER GmbH*, Germany).

The mock-ups investigated are TA6Vα flat samples (length 10 cm, width 5 cm, and depth 1 cm). The defects have a depth of 50 µm. The width varies between 30 µm (sample D2-A) and 100 µm (sample D7-B). The length is 1 mm for D2-A and 0.6 mm for D7-B.

Fig. 6 (a) and (b) show the response signal of the eddy currents inside the material using a TMR-probe for two different test samples, D7-B and D2-A. The test frequencies were 2 MHz for D7-B and 1.3 MHz for D2-A. X- and Y-channels are presented as grey-scaled plots. In addition, we add line strips across the defect (blue line) and along areas having no defect (red line). Besides defect signal we detected wavelike magnetic fields. These fields are caused by the rough polished surface.



(a)



(b)

Fig. 6. Eddy current testing of Titanium samples (TA6Vα) with artificial notches of different sizes using the TMR-probe. Data are presented for each channel as grey-scaled plot (left: X-channel; right: Y-channel). Additional diagrams of recorded data across the notches (red curve) and along a line without a defect signal (blue curve) are above the grey-scaled plots. (a) shows the results of Ti-sample D7-B, notch: $l \times w \times d$ = 600 × 100 × 50 µm³ and (b) of sample D2-A, notch: $l \times w \times d$ = 600 × 30 × 50 µm³.

The SNR for D7-B (defect size $l \times w \times d = 600 \times 100 \times 50$ µm³) is 17.6 dB. For test sample D2-A ($l \times w \times d = 1000 \times 30 \times 50$ µm³) we obtained a lower SNR of 8.0 dB due to the smaller size of the notch. We compared our findings for test sample D7-B with conventional ET-technique. Here, we deployed ET-probe “KDS 2-2” and used a test frequency of 600 kHz. We obtained a SNR of 29.4 dB. This value differs from our results using the TMR-probes. Nevertheless, the MR-probes provide a better spatial resolution and a faster scanning due to their small sensing elements and their build-up as arrays compared to differential probe “KDS 2-2”.

Conclusion

The IMAGIC-consortium developed new ET-probes based on TMR arrays and an ASIC. Here, we combined a high number of small MR-elements (sensing areas in the order of some µm²) with an NDT-adapted ASIC in order to achieve a detection of µm-sized defects with a high spatial resolution. We conducted performance tests of these new probes. For this purpose we measured the eddy current response caused by defects in Ti- and Al-test samples, materials widely used in aerospace industries, and compared our findings with results of conventional ET-techniques.

In case of spatial resolution we achieved a better performance using the new probes in contrast to conventional probes. Here, the small sensing elements are advantageous compared with ET-probes having coils with a diameter of 0.5 mm. Two defects (440 µm-sized boreholes) with a distance of 0.6 mm in between could be resolved. The best commercial ET-sensor deployed in our study resolved defects with a distance of at least 1 mm.

Testing Ti-samples, a material with a low conductivity by contrast with Aluminum, we yielded a slightly better result using conventional ET-techniques. Nevertheless, the use of array-based sensor systems can help reducing testing time by scanning a greater area at once. Additional high spatial resolution makes the MR-based ET-probes an alternative to conventional systems.

Future work will be the use in industrial applications and, therefore, the optimization of the sensing elements and the downstream electronics, i.e. the ASIC and its supporting electronic components.

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