Deep Penetrating Eddy Currents and Probes

Gerhard MOOK, Otto-von-Guericke-University Magdeburg, Germany
Olaf HESSE, IMG Nordhausen, Germany
Valentin UCHANIN, Leotest Medium Center Lviv, Ukraina

Abstract. The eddy current skin-effect limits the detection of subsurface defects and the range of thickness measurement. Traditional concepts to estimate the penetration depth basing on plane wave propagation into a conducting halfspace cannot describe the real depth of inspection achievable by state-of-the-art sensors and instruments. The paper presents a more fruitful concept for estimating the noise limited inspection depth. Here, the traditional parameters like frequency, probe dimensions, conductivity and permeability are analysed in combination with all sources of noise and disturbances in eddy current technique. New low frequency eddy current probes of inductive and magneto-resistive type are presented and characterised. These probes combine deep penetration with comparatively small size and good spatial resolution.

1. Introduction

The eddy current technique is known as an efficient surface and near surface inspection method avoiding any couplant and able to penetrate thick non-conducting coatings. The probes mostly are easy to handle and even mechanical probe guiding and imaging techniques are state of the art. These features bring up new requirements. Why not use this technique for subsurface inspection of cracks, voids, corrosion or other material anomalies? The weak point of eddy currents is their limited penetration into the conducting material. The magnetic field of these currents is counteracting the exciting magnetic field of the probe thus lowering the eddy current density with increasing depth. This behaviour cannot be changed fundamentally but the probes and the inspection parameters can be optimized for maximum penetration.

The following paragraphs analyse the most significant influences on the penetration behaviour of eddy currents and present newly developed deep penetrating probes for application in aircraft maintenance, nuclear and conventional power plants and metal working industry.

2. Standard and effective penetration depth

Fig. 1 compares different definitions of penetration depth. The standard penetration depth δ defines the depth where the eddy current density has decreased down to 1/e of the surface density. At a depth of 3δ the eddy current density decreases to about 5 % of the surface density. The standard penetration depth bases on the assumption of a plane wave behaviour of the penetrating magnetic field. Actually, eddy current probes are far from providing a plane magnetic field.

Following the model of Dodd and Deeds [1] Mottl calculated the decrease of eddy current density analytically [2]. For an air core probe he found that the decrease of eddy current density strongly depends on the probe diameter. With small diameters ($R/\delta \approx 1$) the density decreases according to the dashed line in Fig. 1 and provides significantly smaller

values for the penetration depth (δ_t) compared with the plane wave. Only with rising diameter up to $R/\delta > 10$ the δ-values become similar to δ_t.
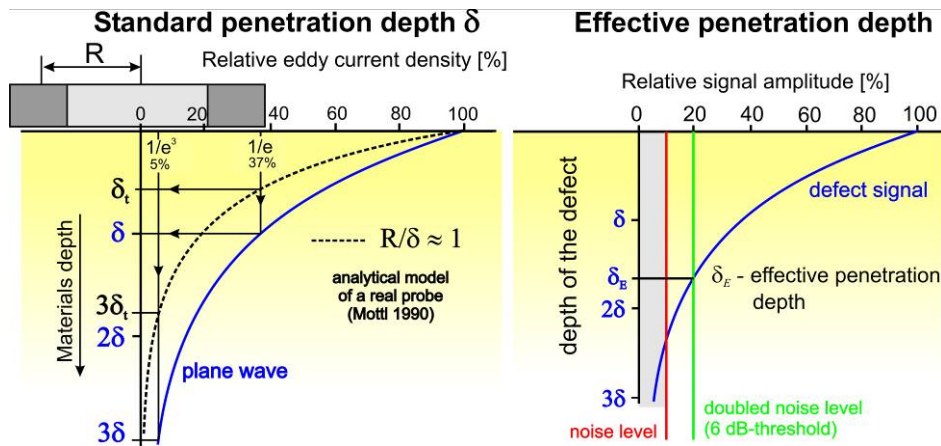

Figure 1. Definition of standard and effective penetration depth

Both values are theoretical values and do not characterize the achievable inspection depth. To fill this gap an effective penetration depth was defined. This is the depth from where eddy current signals can be received with a sufficient signal to noise ratio. Obviously, this depth cannot be calculated in general but depends on the material and the defect to be detected, the instrument and probe parameters and the disturbing influences from the environment.

Fig. 2 illustrates the effective penetration depth for a signal to noise ratio of 6 dB. Mostly the effective depth is much greater than the calculated standard penetration depth.

3. Methods to increase effective penetration depth

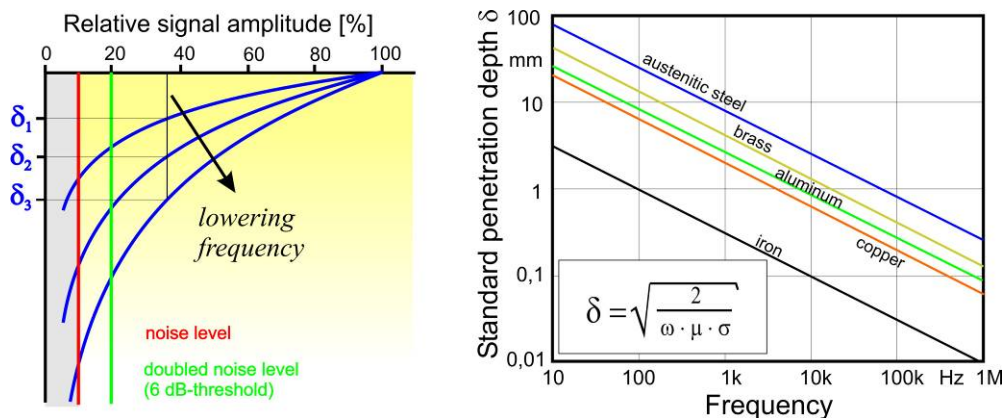### 3.1 Decrease of exciting frequency

Figure 2. Inspection frequency and penetration

Even from the equation for the standard penetration depth and from the derived diagram can be seen that the penetration increases with lowering frequency. On the left hand side of Fig. 3 the decrease of eddy current density is shown for different frequencies. Low frequencies seem to be best suited for hidden defect detection.

This kind of analysis suffers from the representation of eddy current density as the ratio of the absolute density in a defined depth to the surface current density. For the detection of hidden defects the absolute current density is much more important than the relative density. The absolute eddy current density is a function of the field strength and the frequency.

So we have to consider, that with lowering frequency the absolute eddy current density lowers, too, due to the lower rate of magnetic flux alteration.

3.2 Increase of exciting field strength

Another way of increasing the penetration is the increase of field strength of the exciter. This can be achieved, for instance, by stronger current in the exciting coil. The exciting current is only limited by the properties of the coils windings and the thermal and magnetic properties of the flux guides.

To increase the exciting field strength and prevent coil heating the pulsed eddy current technique is used [3, 4]. With constant thermal load the energy of many sine periods is concentrated in one large pulse followed by a break.
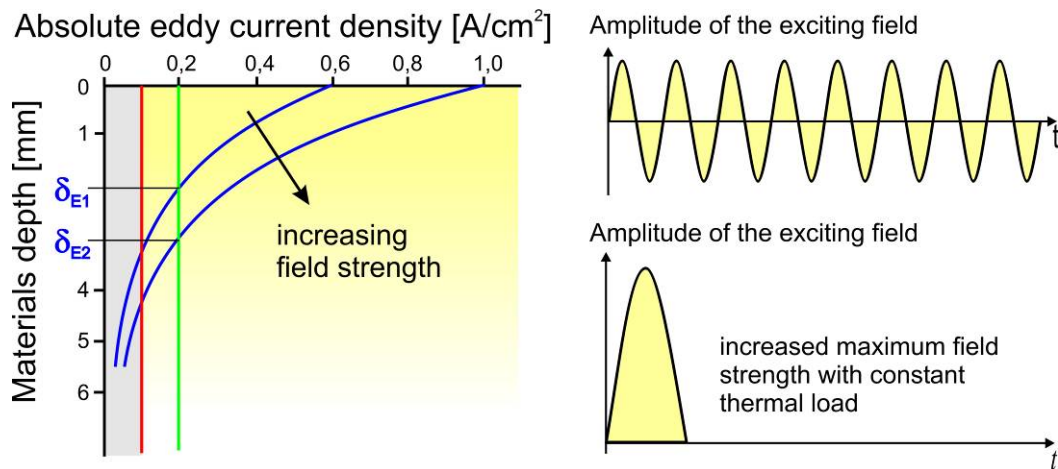

Figure 3. Field strength and penetration

3.3 Selecting deep penetrating field trajectories

The use of non-axial send-receiver probes offers the opportunity to optimize the distance between the transmitting and the receiving coil. These probes sometimes are called half-transmission or remote field eddy current probes. Figure 4 brings up the principle of those probes. The field of the exciting coil penetrates according to the well known rules of alternating field spreading into the material. The receiving coil only picks up this part of the whole flux which has penetrated deeply into the material. The larger the distance between the two coils the deeper the detected flux lines have penetrated the material but the lower becomes the measurement signal. This system of two non-axial coils may be regarded like 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 and the resolution. One has to trade off between these parameters.
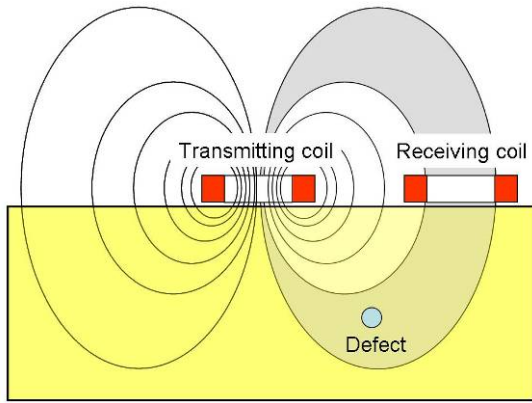
Figure 4. Selection of deep penetrating field trajectories

3.4 Changing material's properties

In some cases the change of the electromagnetic properties of the material under inspection can increase the penetration. Very rarely it is possible to decrease the conductivity and/or the magnetic permeability by heating the material. More often the permeability of ferromagnetic materials can be decreased by a superimposed DC field. Figure 5 illustrates this idea.

The DC field may reduce the incremental permeability downt to μ_0, i.e. the relative permeability decreases to 1. This way, the ferromagnetic material is transformed to a non-magnetic material from the eddy current point of view.
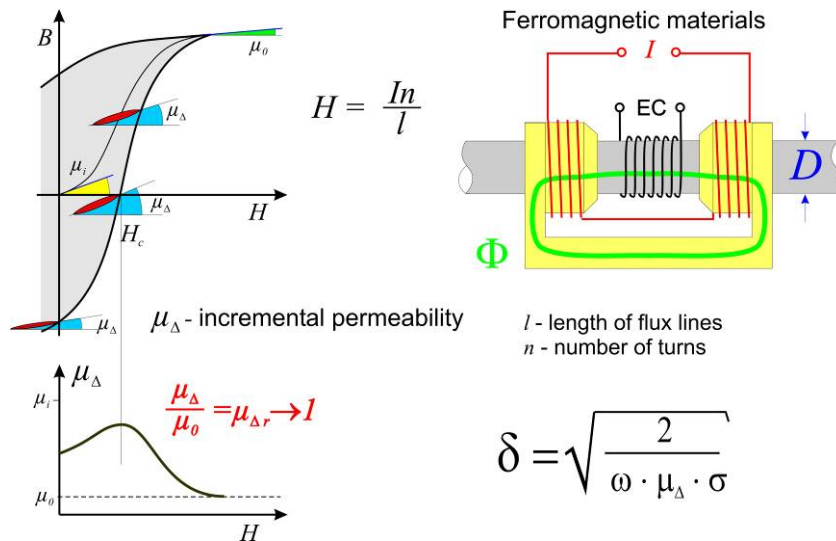

$$H = \frac{In}{l}$$

μ_Δ - incremental permeability

l - length of flux lines
n - number of turns

$$\frac{\mu_\Delta}{\mu_0} = \mu_{\Delta r} \rightarrow 1$$

$$\delta = \sqrt{\frac{2}{\omega \cdot \mu_\Delta \cdot \sigma}}$$

Figure 5. Incremental permeability vs. bias DC field

3.5 Increasing sensor sensitivity at lower frequencies

Sources of noise at eddy current inspection are the exciting signal, the ambient fields, the sensor, the electronic circuitry, the handling systems and in a more common sense the material itself.

Along with choosing a less noisy eddy current instrument (at low frequencies high gain values become necessary) and a sophisticated sensor handling (avoiding vibration of the probe, small lift-off, signal filtering) the sensor itself helps to reduce noise signals.

At lower frequencies common inductive sensors are less advantageous due to the decreasing measurement voltage. The following paragraphs describe the results of optimizing

inductive sensors and the search for alternative solutions by newly developed magnetic DC-field sensors.

4. Deep penetrating eddy current probes

4.1 Improved eddy current sensors with 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

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.

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.

Several sensor layouts with inductive pickup coils were tested. In order to increase the sensitivity of pick-up coils we wound 20 µm enamelled copper wire in 8000 turns on ferrite rods of up to 2 mm diameter and 8 mm length. Figure 6 shows an example.
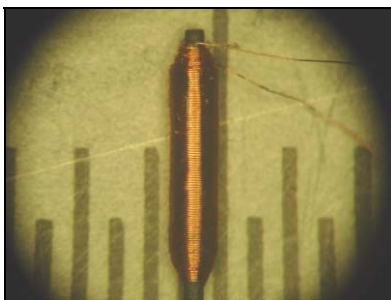

Figure 6. Highly sensitive pick up coil, 0.5 mm diameter, 3 mm length, number of turns about 1000

Such highly sensitive coils can not be used in absolute arrangement because they are very sensitive to environmental electromagnetic noise. This can be overcome by using these elements in well compensated differential arrangements. In this case noise resulting from distant environmental sources will be cancelled while signal changes resulting from material inhomogeneities will result in field gradients detectable by the gradiometric sensing element.
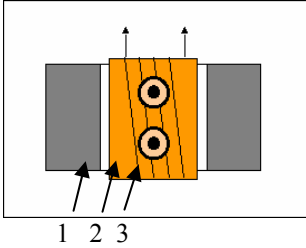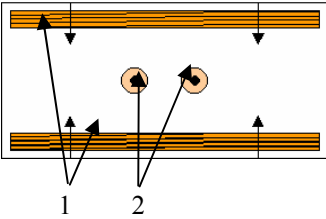
Further it is necessary to avoid direct coupling of the excitation field into the sensing element. This will result in a very small output signal in the case of homogeneous material maintaining high sensitivity to disturbances in the material under test. In this case the dynamic range of the eddy current amplifier can be used more effectively.

In table1 some sensor configurations for low frequency eddy current testing are presented.

4.2 Usage of magnetic field sensors in eddy current probes

As mentioned above the sensitivity of pick-up coils decreases significantly with lower testing frequencies. In this case permanent magnetic field sensors should be considered, e.g. magneto-resistors, Hall elements, flux gate sensors or even SQUID sensors. Very good results on deep penetration eddy current testing were reported using flux gates and SQUID sensors [5-7]. But testing systems described there can hardly be used in real industrial applications because of the complexity and costs of such systems, their insufficient robustness and poor lateral resolution.

Table 1. Sensor configurations for IMG multi-differential eddy current probes

№	Schematic of the probe	Further explanation
01		**Excitation:** U-shaped ferrite yoke with excitation coil **Sensing:** Two pick up coils with number of turns of about 3000 on ferrite rods with 1.2 mm diameter, 5 mm length and magnetic permeability of about 600, the coils are in series with differential orientation. **Legend:** 1 = ferrite yoke; 2 = excitation coil; 3 = differential pick up coils
02		**Excitation:** Two coils with axis parallel to the test surface and differential orientation **Sensing :** Two pick up coils with 3000 turns on 1.2 mm ferrite rods, 5 mm length and μ_r of about 600, the coils are in series with differential orientation; pick up coils of 5000 turns could further increase the sensitivity. **Legend:** 1 = differential excitation coils; 2 = differential pick up coils

In our study we successfully used commercially available AMR and GMR sensors in eddy current probes for low frequency eddy current testing. The additional read out electronics for these magnetoresistive type sensing elements are quite simple and can easily be placed into the sensor housing together with the power supply necessary for sensor excitation and read out electronics. A description of physical principles of function of AMR and GMR magnetic field sensors can be found in [8-10].

For using AMR and GMR sensors in eddy current probes we have to take into consideration the specific function characteristics of these sensors.

4.2.1 AMR sensors in eddy current probes

For AMR sensors we have to keep in mind
- their limited dynamic range,
- 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 read out 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. Furthermore, a more stable sensor covers the dynamic range of the EC read out electronics more effectively.

An integrated sensor module normally used for non-contact current measurement is available. It includes gradiometric layout of the AMR sensing element, zero detection read-out electronics with on-chip field feedback inductors and a sensor stripe pre-magnetisation 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 in Fig. 7. More detailed information about this module can be found in [9].
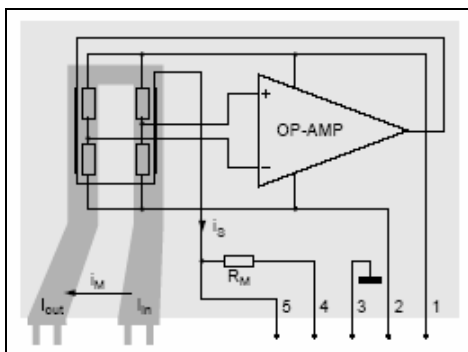
Figure 7. The functional scheme of the module Sensitec CMS2000 [9]

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 gradients. 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. This problem could be solved experimentally, but it is quite difficult to produce a gradiometer module on discrete elements as well compensated and balanced as on the CMS2000 module.

In table 2 some sensor configurations for low frequency eddy current testing using the described AMR sensor module are presented.

Table 2. Sensor configurations for IMG eddy current probes with modified AMR current sensors

№	Schematic of the probe	Further explanation
03		**Excitation:** Inductive coil on top of the module **Sensor:** CMS2000 current sensing module [9]
04		**Excitation:** Yoke with excitation coil **Sensor:** CMS2000 current sensing module [9]

4.2.2 GMR sensors in eddy current probes

Several restrictions have to be kept in mind when using GMR sensors in EC probes:
- their limited dynamic range and quite narrow linear branch of the sensor characteristics,
- the influence of magnetic field variations on the demodulated signal in the sensitive direction of the sensor element,
- the loss of information about the field direction due to the V-shaped sensor characteristics,
- hysteresis of sensor characteristics.

Despite the fact that the field limited resolution of GMR sensors is lower than that of AMR sensors there are advantages of GMR sensors, which make them interesting for the application 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 GMR sensors in EC probes it is 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.
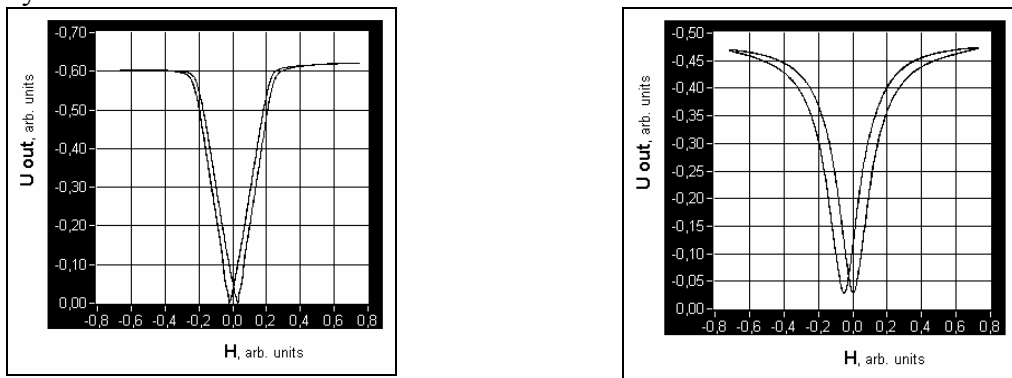

Figure 8. Sensor characteristics example of two commercially available GMR sensors

As we can see from the sensor characteristics of two commercially available GMR sensors (Fig. 8), it is difficult to balance them in gradiometric arrangement due to the non-linearity of their sensor characteristics and hysteresis.

In table 3 some sensor configurations for low frequency eddy current testing using GMR sensors are presented.

Table 3: Sensor configurations for IMG eddy current probes with GMR sensors

№	Schematic of the probe	Further explanation
05		**Excitation:** Inductive coil around the GMR sensor **Sensor:** GMR sensor NVE AAH002-02 [10]
06		**Excitation:** Two coils with axis parallel to the test surface and differential orientation **Sensor:** GMR sensor NVE AAH002-02 [10]

4.3 Practical Results

4.3.1 Test Specimens

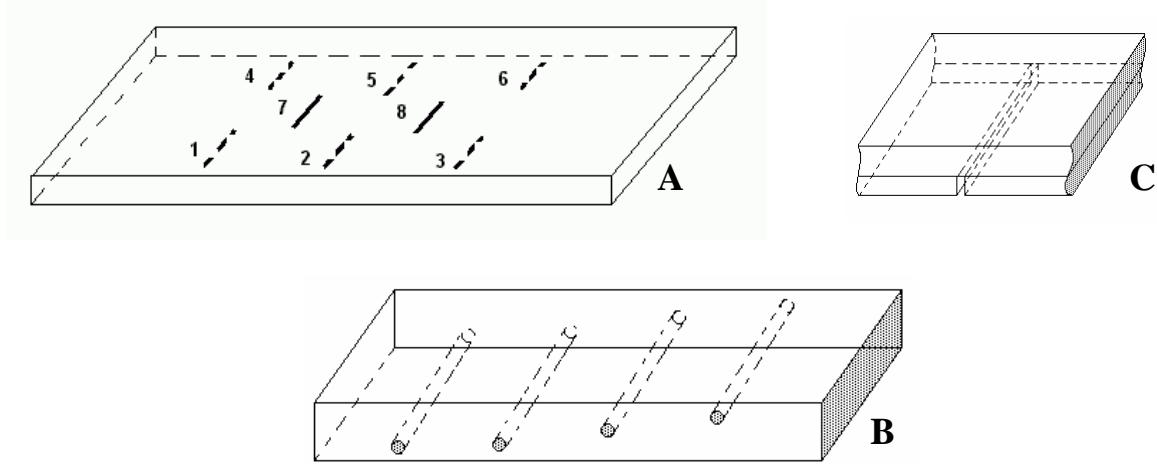The performance of different sensors was tested on specimens shown in Fig. 9.

Figure 9. 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 at depth 2.5 / 5 / 7.5 / 10 mm, C – border line between two aluminium plates through aluminium plates of various thickness placed on top

4.3.2 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. The input of the demodulator consists of a differential amplifier with input resistance of several kOhms. 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.

4.3.3 Test results

<u>Inductive Coils</u>

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.

Figure 10 shows results of testing the above-described 3 test situations. All test slots at the bottom surface of the aluminium test specimen 1 (Fig. 9) could be detected (Fig. 10a). Holes parallel to the surface in the test block 2 at a depth of 10 mm can be seen on EC images of this test block (Fig. 10b). The borderline of 2 aluminium plates could be detected through another aluminium plate on top with a thickness of 15 mm (Fig. 10c).
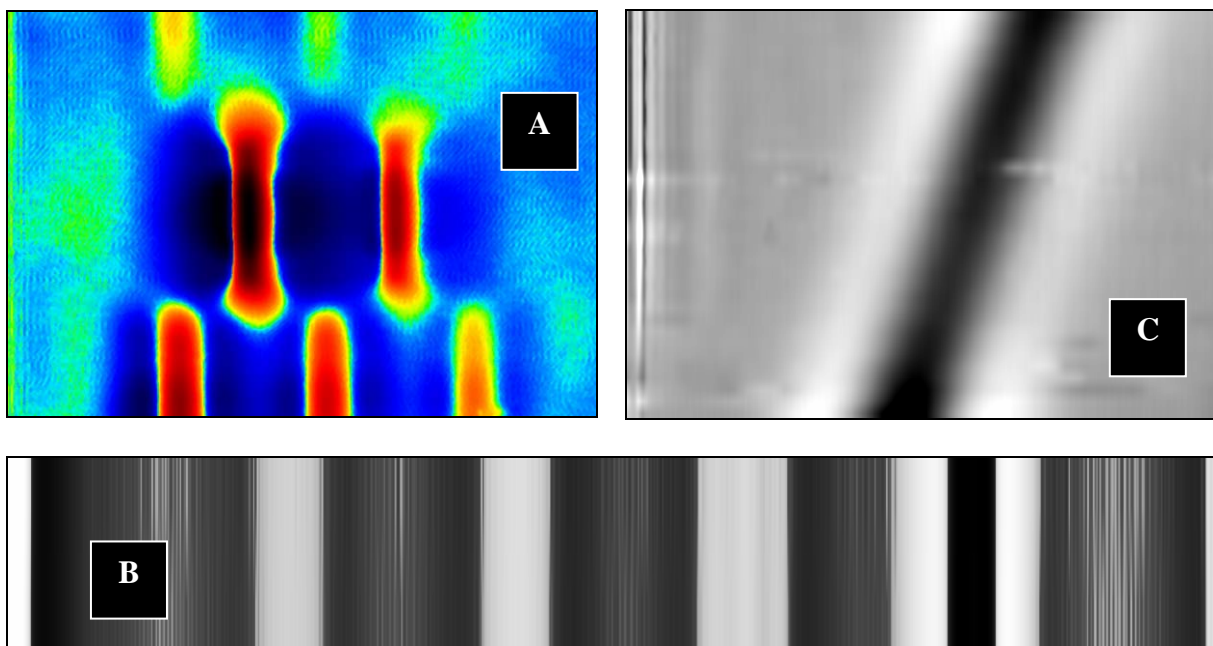
Figure 10. Testing results for situations of Fig. 9 in case of inductive coils usage

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 GMR and inductive sensors.
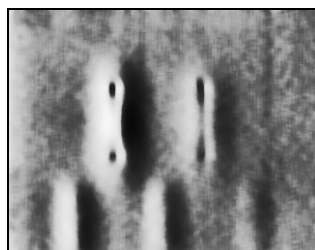

Figure 11. Testing results for situation A of Fig. 9 in case of AMR modules usage

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 GMR sensor type has not been very successful yet, probably because of their very non-linear behaviour.
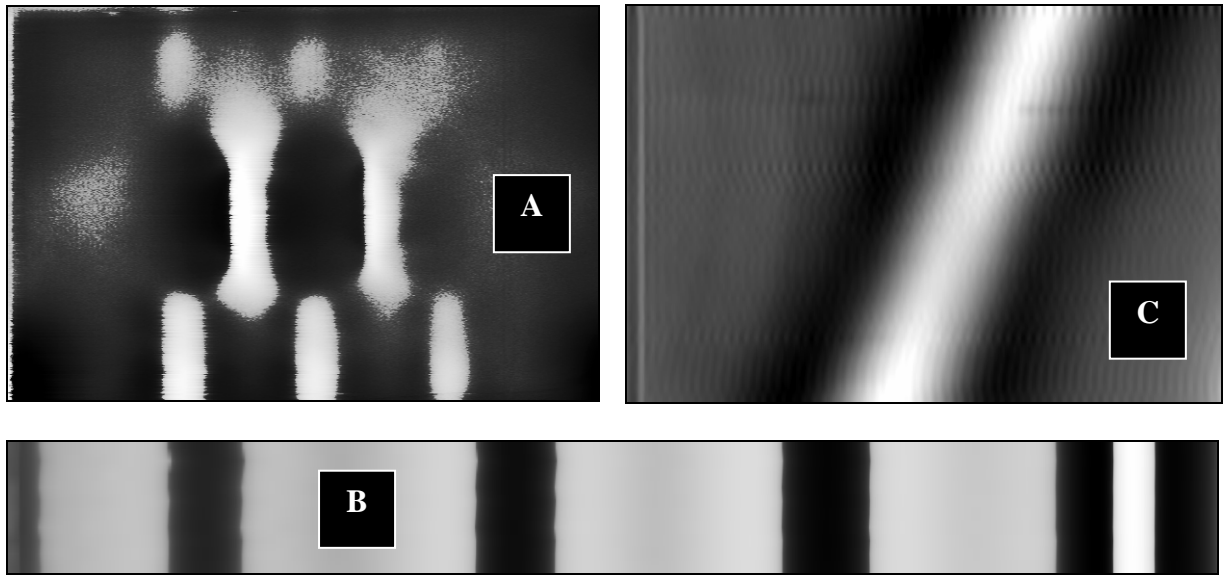
Figure 12. Testing results for situations on Fig. 4 in case of GMR sensors usage

Figure 12 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. 12a). Through holes in the test block 2 at a depth of 10 mm can be seen on EC images of this test block (Fig. 12b). The borderline of 2 aluminium plates could be detected through another aluminium plate on top with a thickness of 15 mm (Fig. 12c).

5. Low-frequency deep penetrated eddy current probes with inductive coils

5.1 Features of the probes

In our previous papers the LEOTEST family of low-frequency eddy current probes with multi-differential secondary coil joining, designed in "Leotest-Medium" Center (Lviv, Ukraine), were presented [11-15]. In these papers some features of designed probes were defined, such as:
- high sensitivity with sharp response to long cracks and to local flaws, such as pore or pitting,
- high penetration and detection of underlying defects,
- good lift-off compression and high spatial resolution,
- good sensitivity to flaw with large distance between probes and tested surface or large thickness of dielectric protection coating.

It is very important that good penetration features were obtained for probes with comparatively small size. We declare this feature as a high ratio of penetration to probe size. We suppose that this parameter is very important and determinant for some practical applications, especially in aircraft constructions with small distance between fasteners.

The LEOTEST family EC probes designed for different applications are adapted with Lemo or Fischer connectors applicable for different EC devices, such as: ELOTEST family produced by Rohmann, Fraunhofer Institute MFEC1-4 device, different devices developed by Dr. Forster Institute, EddyMax produced by Test Maschinen Technik (TMT) devices and universal eddy current devices OKO and VD 3-71, developed in Ukraina by Promprylad (Kiev) [11, 12, 15, 16]. The designed probes were successfully used for deeply underlying flaws, for example:
- the detection of different flaws in inner parts of multi-layer aircraft constructions,

- the detection of flaws in ferromagnetic tubes and welds that are covered with thick protection layers and in aluminium aircraft wings from the inner surface without sealing removal,
- the detection of cracks in inner layers in multi-layer aircraft constructions under different type fastener heads,
- the detection of the deeply underlying pores in copper canisters,
- the detection of subsurface cracks in 15 mm thick stainless steel tubes [15-20].

Last years some new low frequency eddy current probes with excellent penetration features were designed [21, 22]. Today we have a wide range of LEOTEST family low frequency probes with working surfaces from 5 to 33 mm. Coil size, penetration and spatial resolution can be optimised for the application [15].

5.2 Investigation into the ultimate depth of inspection

Let us consider the limits of eddy current probes to detect subsurface flaws using the concept of quasi-infinite crack [22]. A special specimen with artificial quasi-infinite crack was created (see Fig. 13). The specimen consists of two parts: the bottom aluminium alloy plate with flaw installed on the base made from the same material and upper sandwich type part. The artificial flaw was created by mechanical matching of two finely milled and grinded D16T aluminium alloy plates. The artificial crack width is negligible like in real fatigue cracks. The plate thickness and the corresponding crack depth were 25 mm, i.e. deep enough for further crack depth enlargement. Bottom sides of the plates do not influence the signal response. The created artificial crack was oriented perpendicular to the tested sample surface. The length of artificial quasi-infinite crack is much larger then the eddy current probe diameter. This way the influence of flaw size (depth and length) on the signal response was eliminated. These features of the artificial flaw allow calling the flaw a "quasi-infinite crack". This quasi-infinite crack was covered by upper sandwich type part consisting of 0.9 mm thick D16T aluminium alloy sheets. The quantity n of sheets on top of the crack was changed from 0 to 32 to simulate different depth of flaw underlying (H_r).
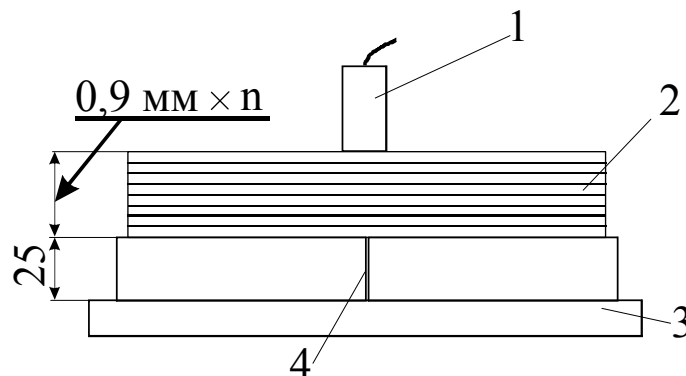

Figure 13. The specimen with quasi-infinite crack: 1 - Eddy current probe, 2 - the set of n sheets defining H_r, 3- the specimen base, 4 - quasi-infinite crack.

Two low frequency eddy current probes developed in Leotest-Medium Center were investigated - Leotest MDF 1701 and Leotest MDF 3301. The Leotest MDF 1701 and MDF 3301 probes have a working surface diameter of 17 and 33 mm, respectively. To estimate the limiting underlying depth of detectable flaws the limiting noise concept was used [13]. The number of covering sheets was increased step by step to observe the signal behaviour of the quasi-infinite crack. The noise signal was also investigated and compared with the flaw signal by scanning the sandwich specimen in the flaw-free region. With increasing

flaw underlying depth the complex plane was rotated to adjust the flaw signal to be oriented in vertical direction.

Figure 14 presents the signal responses in complex plane obtained with MDF 1701 probe on operational frequency of 100 Hz. These signals were obtained with computerized EDDYMAX eddy current card produced by Test Maschinen Technik (Schwarmstedt, Germany). In the upper part of Fig. 1 complex plane signals are presented. The bottom part of Fig. 14 and Fig. 15 presents chart diagrams of the signal's Y-component to estimate the signal to noise ratio. On Fig. 14b and 14c the amplifier gains are the same and were adjusted in vertical (Y) direction 6 dB larger than in Fig. 14a.
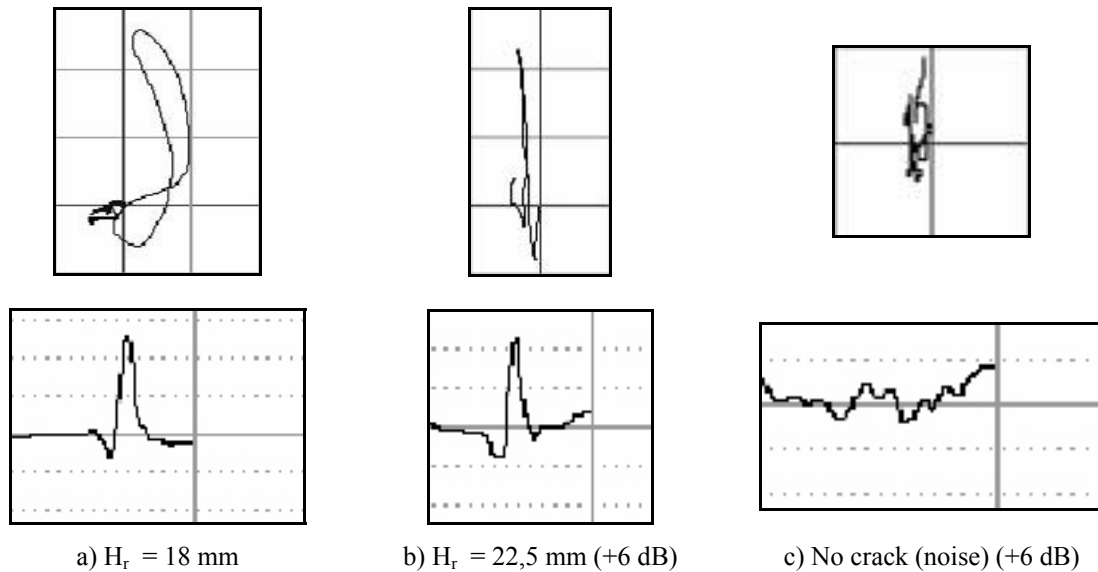

a) H_r = 18 mm   b) H_r = 22,5 mm (+6 dB)   c) No crack (noise) (+6 dB)

Figure 14. The signal responses of MDF 1701 probe with flaw underlying of 18 mm (a); 22.5 mm (b) and for specimen without crack (c).

Figure 15 presents the signal responses in the complex plane obtained with MDF 3301 probe at an operational frequency of **7**0 and 50 Hz. The signals in Fig. 15b, c were additionally amplified by 6 dB in comparison with the signal in Fig. a.

a) H_r = 23.4 mm   b) H_r = 27.9 mm   c) H_r = 28.8 mm   d) No crack (noise)
(70 Hz)   (70 Hz, +6 dB)   (50 Hz, +6 dB)   (50Hz, +6 dB)
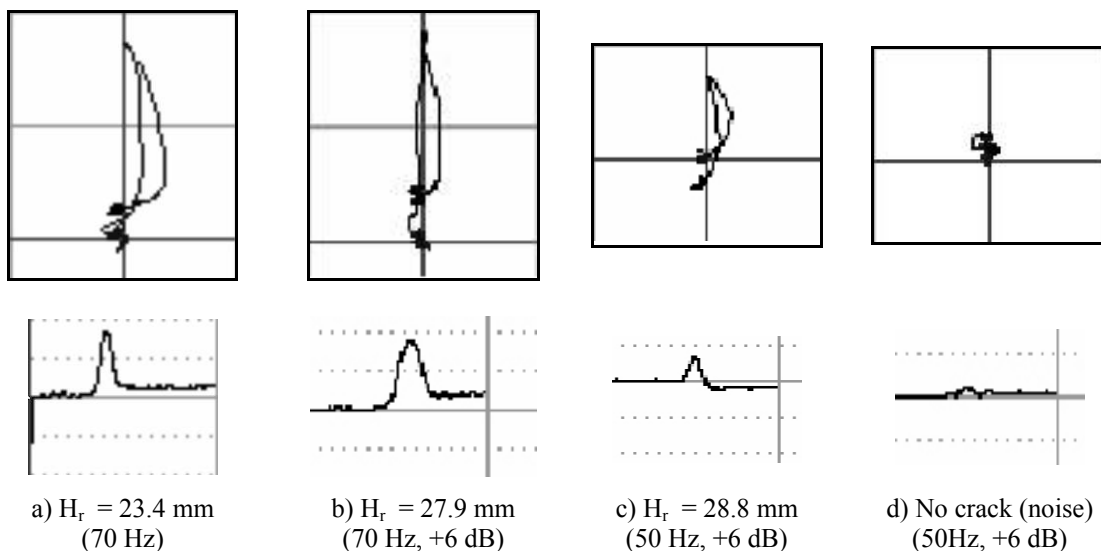
Figure 15. Signal responses of MDF 3301 probe with flaw underlying of 23.4 mm, 70 Hz (a); 27.9 mm, 70 Hz (b); 28.8 mm, 50 Hz (c) and for specimen without crack, 50 Hz (d).

According to the noise limited penetration depth concept the presented results allow estimating the ultimate underlying depth of detectable flaws. For reliable crack detection a signal to noise ratio of more than 6 dB was supposed. We can see that the amplitude of signal response for MDF 1701 probe from quasi-infinite cracks under the 25 sheets ($H_r = 22.5$ mm) is approximately 6 dB larger than noise. This way, the ultimate underlying depth of cracks for MDF 1701 probe can be estimated as 22.5 mm. For MDF 3301 probe at a frequency of 50 Hz the ultimate underlying depth of detected crack can be obtained from the comparison of the results presented in Fig. 15c and 15d and is estimated as 28.8 mm.

5.   Conclusions

The effective depth of penetration depends on the instrument, the probe, the environment and on the flaw to be detected. It cannot be described by the standard depth of penetration basing on the plane wave theory but has to be evaluated experimentally using test specimens.

Opportunities to increase the effective depth of penetration are offered by increasing the eddy current density and the lowering of density decrease. On the receiver side new perfectly balanced inductive sensors and magneto-resistors allow using lower frequencies. Effective penetration depth of more than 25 mm in aluminium alloys can be achieved.

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