Deep Penetrating Eddy Currents and Probes

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.

Standard and effective penetration depth

Figure 1 compares different definitions of penetration depth. The standard penetration depth \( \delta \) defines the depth where the eddy current density has decreased down to \( 1/e \) of the surface density. At a depth of \( 3\delta \) the eddy current density decreases to about 5% of the surface density. The standard penetration depth bases on the assumption of plane wave propagation into a conducting halfspace. 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 \( R/\delta (\delta \approx 1) \) the density decreases according to the dashed line in Figure 1a and provides significantly smaller values for the penetration depth \( \delta_r \) compared with the plane wave. Only with rising diameter up to \( R/\delta > 10 \) the \( \delta_r \) values become similar to \( \delta \).

Both values are theoretical values and do not characterize the achievable in-
spection 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.

Figure 1b 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.

Methods to increase effective penetration depth

Decrease of exciting frequency
Even from the equation for the standard penetration depth and from the derived diagram in Figure 2b can be seen that the penetration increases with lowering frequency. Figure 2a depicts the decrease of eddy current density 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.

Increase of exciting field strength
Another way of increasing the penetration is to increase the 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 4 brings up the principle of those 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 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 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.

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 down to \( \mu_0 \), i.e. the relative permeability decreases to 1. This way, the ferromagnetic material is transformed into a non-magnetic material from the eddy current point of view.

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 seem to be 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.

Deep penetrating eddy current probes

Improved inductive pick-up coils

Although inductive pick-up coils show decreasing sensitivity at lower frequencies they can successfully be used for sensitive low frequency eddy current testing. There are several means for increasing the sensitivity of inductive pick-up coils. Larger coil diameter increases the coupling flux with the material and brings the field nearer to the plane wave but lowers the lateral resolution. The increase of the number of turns demands very thin enamelled copper wire with down to 20 \( \mu \)m diameter. An example of a pick-up coil with 1000 turns is shown in Figure 6. Additionally, well compensated differential arrangements of pick-up coils guarantee the optimal usage of the dynamic range of the read out electronics. A special shielding may lower the influence of external electromagnetic noise sources.

The usage of inductive pickup coils has some clear advantages over the magnetic field sensors. They perform very linear, they only have a very small hysteresis and they do not saturate even at quite large excitation levels. That permits high flexible sensor configurations. Last not least inductive coils may be easily adapted to commercial eddy current instruments.

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.

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 well compensated differential arrangements. Noise resulting from distant environmental sources will be cancelled while material inhomogeneities will produce 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. Figure 7 displays some sensor configurations for low frequency eddy current testing.

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 dc-field sensors should be considered, e.g. magneto-resistors, Hall elements, flux gates or even SQUIDs (superconducting quantum interference devices). Very good results on deep penetration eddy current testing were reported using flux gates and SQUIDs [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.

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.

Anisotropic magneto-resistive sensors

For AMR (anisotropic magneto-resistive) 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 and 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.

This situation can be overcome by following means. First, use these sensors with zero detector read out electronics (negative magnetic field feedback); second, substitute absolute arrangements by gradiometric of at least two sensing elements; third, apply a stabilising magnetic field with direction perpendicular to the sensitive direction and in plane with the permalloy sensor stripes; fourth, avoid direct coupling of the excitation field to the sensing element.

An integrated sensor module normally used for non-contact 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 pre-magnetisation by calibrated permanent magnets precisely placed onto the sensor module. The module has an acceptable size for
The functional scheme of the module is shown in Figure 8a.

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 disturbance because the defect produces 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 with greater underlying 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. Figure 8b and 8c describe some sensor configurations for low frequency eddy current testing using the described AMR sensor module.

### Giant magneto-resistive sensors

Several restrictions have to be kept in mind when using GMR (giant magneto-resistive) sensors in eddy current probes. First, the dynamic range is limited and only has a quite narrow linear branch; second, the influence of magnetic field variations on the demodulated signal in the sensitive direction of the sensor element; third, the loss of information about the field direction due to the V-shaped sensor characteristics; fourth, the hysteresis of sensor characteristics.

Despite the lower field limited resolution of GMRs compared to AMRs there are promising advantages for eddy current applications. They are insensitive to magnetic fields perpendicular to their sensitive direction and their characteristics do not depend on strong magnetic fields the sensor is exposed to. More robust eddy current probes for noisy industrial environment may be expected.

For GMR sensors in eddy current probes it is desirable to work in gradiometric arrangement and with zero detection read out electronics. Furthermore, a biasing dc-field reduces non-linear distortions in the output signal and maximises the ac-field sensitivity.

The characteristics of commercially available GMRs of one type differ significantly, so it is difficult to balance them in gradiometric arrangement. Additional problems result from the non-linearity of their characteristics and the hysteresis.

Figure 9 depicts some sensor configurations for low frequency eddy current testing using GMR sensors.

### Experimental Results

All eddy current probes were tested with three reference pieces containing different open and hidden defects. For imaging a stepper driven 2D-scanner was used.

Figure 10 compares the results of the inductive and the GMR sensor at an aluminium sheet with open and hidden slots. Best results could be obtained with a differential inductive eddy current probe using two well-compensated inductive coils with number of turns of 8000 each. Working frequencies of down to 350 Hz were used for deep penetration. All slots could be detected.

Good results could be obtained by 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.

Nevertheless, the signal-to-noise-ratio of the inductive sensor is better than that of the GMR sensor.

The second reference piece was a hidden gap between two 2 mm aluminium sheets under 15 mm aluminium coverage. Figure 11 shows that both the inductive and the GMR sensor are able to visualize the gap.
The AMR modules were used in our first attempt to integrate industrial available magnetic field sensors into eddy current probes. Due to some specifics of these modules we obtained rather good but not overwhelming results, which were much improved by GMR and inductive sensors.

The third reference piece was an aluminium block with holes parallel to the surface. The eddy current images are shown in Figure 12. Again both the inductive and the GMR sensor brought up all defects.

Multi-differential eddy current probes with inductive pick-up coils

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 [8-11]. The most attractive features of this type of probes are its high sensitivity to long cracks and local flaws like pores and pitting, its high penetration and detection performance for hidden defects, its good lift-off compensation and high spatial resolution and its good sensitivity to flaws under very thick dielectric protection coating.

The good penetration features were obtained for probes with comparatively small size. We define 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 structures with small distance between fasteners. The LEOTEST probes can be connected to commercial eddy current instruments and have shown their outstanding performance in many applications like the detection of different flaws in inner parts of multi-layer aircraft structures, the detection of flaws in ferromagnetic tubes and welds covered with thick protection layers, aluminium aircraft wings from the inner surface without sealing removal, the detection of cracks in hidden layers in multi-layer aircraft structures under different type of fastener heads, the detection of the deeply underlying pores in copper canisters and the detection of subsurface cracks in 15 mm thick stainless steel tubes [12-16]. The probe design and its Point Spread Function is shown in Figure 13.

Figure 14 presents an eddy current image obtained by 2D-scanning a specimen with hidden flat bottom holes of 4 mm diameter. The Point Spread Function of the probe produces a highly significant pattern of up to 6 mm underlying.

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 [17]. Figure 15 presents a special specimen with artificial quasi-infinite crack. 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. Mechanical matching of two finely milled and grinded D16T aluminium alloy plates created the artificial flaw. 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 growth. Bottom sides of the plates do not influence the signal response. The artificial crack was oriented perpendicular to the tested sample surface. The length of this crack is much larger then the eddy current probe diameter. That way, the influence of flaw size (depth and length) on the signal response was eliminated. These flaw features allow calling it a quasi-infinite crack. This quasi-infinite crack was covered by upper sandwich type stack 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 (Hr).

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 concept of noise limited penetration depth was used. The number of covering sheets was increased step by step to study the signal behaviour of the
The ultimate underlying depth of detectable flaws. For MDF 1701 probe at 100 Hz with flaw underlying of 18 mm and 22.5 mm compared to noise signal quasi-infinite crack. The noise signal also was investigated and compared with the flaw signal by scanning the sandwich specimen in the flaw-free region. With increasing flaw underlying the complex plane was rotated to adjust the flaw signal to be oriented in vertical direction.

Figure 16 presents the signal responses in the complex plane obtained with MDF 1701 probe at an inspection frequency of 100 Hz.

In the upper part of Figure 16 the complex plane signals are presented. The bottom part of Figure 16 chart diagrams of the signal’s Y-component is shown to estimate the signal-to-noise ratio.

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 cannot be described by the standard 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 density decrease with increasing depth. On the receiver side new perfectly balanced inductive sensors have handling and performance advantages over AMR and GMR sensors. The advantage of GMR sensors is the price and the readiness for sensor arrays.

### Conclusions

The effective depth of penetration is limited by the noise signal and 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.

**References**

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### Abstract

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