Towards Material Characterization and Thickness Measurements using Pulsed Eddy Currents implemented with an Improved Giant Magneto Resistance Magnetometer

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Abstract. Standard Pulsed Eddy Current Systems, as RTD-INCOTEST© equipment, use receiver coils to measure eddy current decay in conducting objects. Advantages of full coils, as sensor for the eddy current, are its simple construction and the possibility of eddy current focussing. But, some disadvantages are the high induction voltage due to a large pulsed signal, the large sensor area and the low coil's sensitivity especially at large times. Some of these disadvantages can be avoided by using a magnetic-field sensor instead of a coil and some advantages also appear. Recent developments in Improved GMR Magnetometer open a new possibility to measure the decay by means of magnetic-field measurement. The present paper focuses on recent theoretical and practical investigations made by RTD and his partners. The measurement method is presented and discussed in comparison with the theoretical signal behaviour. Experimental features are investigated and the practical feasibility of the technique is shown. Furthermore, an analysis is presented enabling the simultaneous determination of both material properties and thickness with an optimal fitted function. For several types of Carbon steel materials, a good accuracy of their properties (permeability, conductivity, and thickness) can be achieved. Recommendations for further development are also given.

Introduction

The RTD-INCOTEST© method utilises a coil as sensor to measure a time-varying magnetic field. This field is the result of eddy currents created in a conducting object by means of a transmitter coil [1-3].

Advantages of using a coil as sensor for the eddy currents are the simple construction, the huge dynamic range (160..200 dB/√Hz, for 10 kHz … 0.1 Hz) and the possibility of focussing the sensor. Some disadvantages are the high induction voltage at the start of the signal, the large area of the coil and the coil's sensitivity to the time derivative of the magnetic field. These disadvantages can be avoided by using a magnetic-field sensor instead of a coil. Up to now this has not been possible because with traditional magnetic-field sensors the dynamic range was not large enough (i.e. Hall sensors) or the techniques were difficult or expensive (i.e. Squids). The development of the GMR sensor [4-7] overcomes these restrictions and facilitates their use as sensors in the RTD-INCOTEST© system, as we present here.

This paper is organised as follows. The mains principle of operation is summarized in part 1. Parts 2, 3 are, respectively, dedicated to experimental measurements with GMR sensors and simultaneous determination of both material properties and thickness, followed by a conclusion.

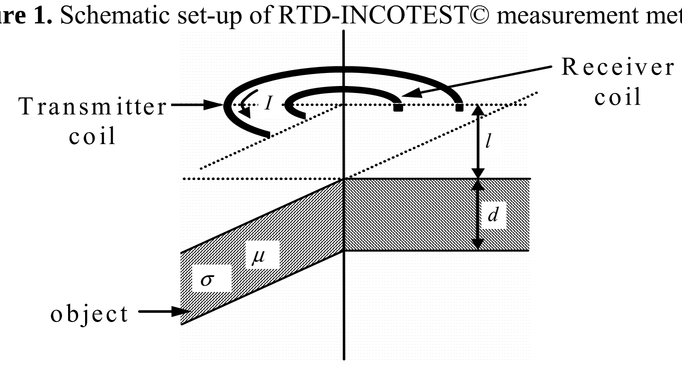
1. Principle of Operation

The pulsed eddy current method RTD-INCOTEST© is based on measurement of an induction voltage in a receiving coil as function of time. This voltage is created by the slowing down of the eddy currents generated in the object by means of a suddenly switched off current, *I* through a transmitting coil (see figure 1) at a lift-off, *l* above the object. After data processing this signal is processed to fit to a model with several parameters representing the material properties (μ permeability and σ conductivity) and object thickness (*d*). This model is given by a simplified formulation [1, 3]:

$$U_c(t) = \frac{A_c \tau^{-3/2}}{1+\frac{t}{\tau_g}} \Theta\left(\frac{t\text{-}t_d}{\tau}\right) \text{ where } \Theta(x) = \sum_{i=1}^{\infty} i^2 \pi^2 e^{-i^2\pi^2 x} \qquad (1)$$

$U_{Coil}(t)$ is the induction voltage (corrected for the self induction) as a function of time, t, A_c the amplitude, τ a time constant and t_d a delay time, A_c and τ_g are coil geometry, lift-off and object properties dependent. Typical behavior for the signal is a decay according to an inverse power law at small times and after a certain time exponential decay sets in as the red full line shown in figure 2.

Figure 1. Schematic set-up of RTD-INCOTEST© measurement method.



So, the thickness of the object can be determined by comparing the measured signal to a reference measurement of a known thickness [1]. Taking a reference measurement of an object with a known thickness is equal to determining the product of $\mu\sigma$. Obvious disadvantage of the method is the need for a reference measurement. Nevertheless, in certain cases this disadvantage can be overcome [2, 3]. Other obvious disadvantages are the large area needed for the sensing coil, reducing its sensitivity to small defects and the high induction voltage due to the sudden switch off of the transmitter current. Further, the induction voltage in the receiver coil is proportional to the change of the magnetic field in time, reducing the sensitivity at larger times.

All these disadvantages can be solved by using a magnetic-field sensor instead of a coil (see figure 3). The signal behaviour of a magnetic-field sensor corresponds to the integral of the induction signal eq. (1) of a coil receiver. Similarly, it can be approximated by:

$$U_{GMR}(t) = C\left[A_{GMR}\tau^{-1/2}\Xi\left(\frac{t\text{-}t_d}{\tau}, \frac{\tau_g}{\tau}\right) + S(t)\right], \tag{2}$$

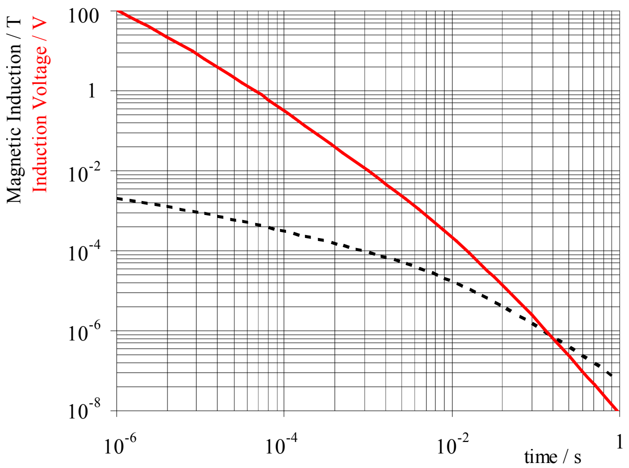
$$\Xi(x,y) = \sum_{i=1}^{\infty} i^2\pi^2 e^{i^2\pi^2 y} E_1\left[i^2\pi^2(x+y)\right],$$

where E_1, the exponential integral

$$E_1[x] = \int_x^{\infty} \frac{e^{-t}}{t}\,dt$$

is used as the integration of equation (1). $U_{GMR}(t)$ is the sensor signal as function of time corrected for the signal if no object is present, C the sensitivity of the sensor in V/T, A_{GMR} a measure for the amplitude of magnetic field, τ, τ_g and t_d are the same kind of parameters as described for the coil. The term $S(t)$ is a function depending on the magnetic-remanence properties of both sensor and object material. Expected signal example of a magnetic-field sensor is shown as the dashed black line in figure 2.

Figure 2. Typical response of a very thick conducting object for pulsed eddy current voltage signal with coil as receiver (full red line) or, for pulsed eddy current field signal with magnetic field sensor as receiver (dashed black line), respectively, $U_{Coil}(t)$ and $U_{GMR}(t)/C$. Note the logarithmic scales.



The detailed behaviour of pulsed eddy current induced signals was first studied by Dodd *et al* [8] and extended to the time domain, for instance, by De Haan *et al* [2] and extended to magnetic field sensors in Dolabdjian *et al* [9].

2. Measurements with GMR sensor

The Pulse Eddy Current System consists of the combination of an Improved Giant Magneto Resistance Magnetometer (IGMRM) [5-7] and two classical coils surrounding the magnetometer (see figure 3). The coil characteristics are given in table 1.

The second coil with the largest diameter is used to focus the eddy currents in the object in the lateral direction. The magnetometer sensing axis is orthogonal to the sample surface and placed at the coils centre axis at a distance to the surface of l_r. The IGMRM performances are summarized in table 2 and complementary information will be found in [5-7]. A more extended description is given in [9]. Measurements on a thick aluminium cylinder with a height of 10 cm and a diameter of 15.4 cm compared to theoretical calculations are shown in figure 4. The current was measured to be 0.176 A (± 0.5 %). Here and in the following, the sensitivity of the sensor was fixed to 1003.7 V/T, yielding a conductivity of $2.24 \cdot 10^7$ S/m and a receiver height of 7.1 mm. The aluminium conductivity was taken the same as in previous measurements [2]. The correspondence of the measurement and the fit is very good up to 10 ms.

Figure 3. Dimensions of real-live transmitting/receiving antenna.

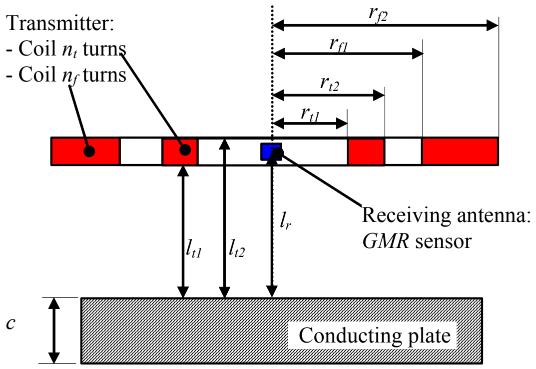


Table 1. Dimensions of transmitter-receiver system as used in calculations and/or measurements.

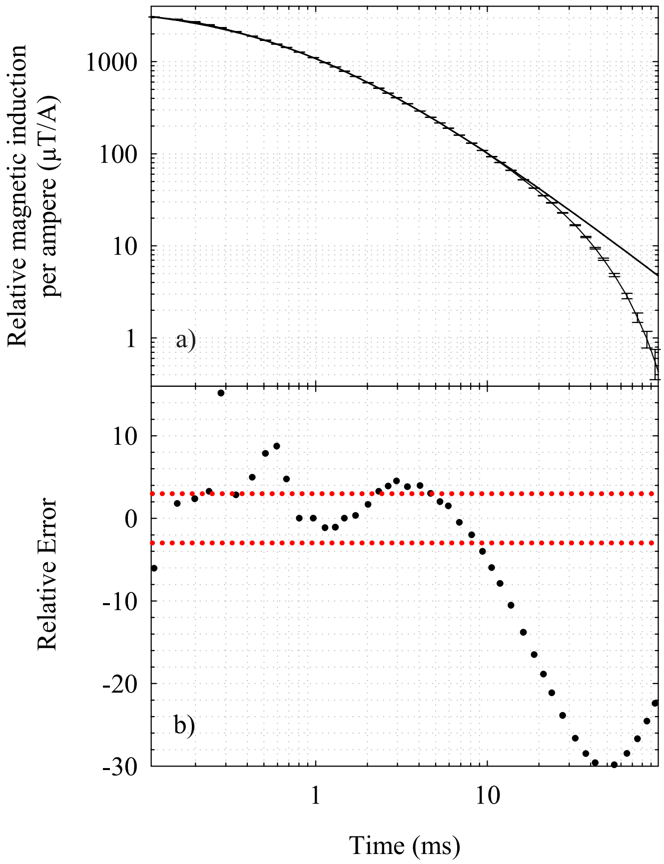
	l_r (mm)	l_{i1} (mm)	l_{i2} (mm)	r_{i1} (mm)	r_{i2} (mm)	n	I (A_{peak})
Transmitter Coil (t)		4.5	7.5	10.5	15.0	500	I
Transmitter Coil (f)		4.5	7.5	19.5	20.5	80	-I
Receiver GMR sensor	7.1						

Table 2. Improved GMR Magnetometer performances.

	Improved GMR magnetometer
Supply voltage	± 12 V
First stage gain output sensitivity	≈ 1,000 V/T
Bandwidth	dc to > 300 kHz
Slew-rate	Theoretical > 160 T/s Measured >37.5 T/s*
Distortion (Total Harmonic Distortion): F = 10 Hz - 1 kHz	Amplitude: ± 1mT_{peak} < 0.03 %* Theoretical : < 0.001%
Noise density	5/√f nT/√Hz f< 1 kHz ≈ 50 pT/√Hz f > 1 kHz
Dynamic: F = 10 Hz - 100 Hz - 1 kHz	143 - 153 - 163 dB/√Hz
Maximal Full Scale field range	± 12 mT
Spatial resolution	< 1 mm** Limited by the encapsulation
Hysteresis	Negligible
Perpendicular field sensitivity	Cos(β)**
Operating temperature range	-40°C to + 85°C*
Insensitivity to magnetic shock	> 40 mT
Encapsulated sensor external size	0.7 mm × 0.7 mm × 4 mm

* Results limited by the measurement system dynamic and linearity
** Datasheet or Measured

Figure 4. Measured magnetic induction above an aluminum cylinder (a) reduced to a current of 1 A as function of time (dots) and fit with $\sigma = 2.24\ 10^7$ S/m (line) and relative error of fit compared to the accuracy of the measurement (b). In figure (b), horizontal lines (±3) give the model confidence interval of 99.73 % of a normal distribution.



After this time, the fit starts to deviate from the measurements. This is due to the limited size of the aluminium cylinder used for this measurement. Measurements were also done with the system put in the centre on top of four iron step wedges. All 3 steps of the wedges had a width and length of 16.5 cm. The current during the measurements was 0.180 A (± 0.5 %). As iron plates have some remanence, normally the signal will not vanish for long times, but will become constant or only varying very slowly compared to the times considered here. It is assumed that at the end of the measuring interval (400 ms in the measurements) the magnetic remanence is stable. The fitted parameters are shown in table 3. The measurements and fits are shown in figure 5. The measurement accuracy was, also, about 1 %. Note the rapid decrease after a certain time depending on the thickness of the plate. The correspondence of measurements and fits is good. The reported deviation at large times for aluminium does not occur here, because of the lesser extension of the eddy currents in the lateral direction for iron and the larger dimension of the steps, similarly as in [3]. Note the difference in amplitude and bending point of the signals due to the difference in material properties. From table 3, it is clear that the variation in material properties is quite large for a single step wedge. These variations can be due to several effects, like the machining or magnetization history of every single step.

3. Simultaneous determination of both material properties and thickness

It is possible to use the above measurement method to determine both the thickness and the material properties separately. This can be done by looking into more detail to the signal. First, the amplitude of the signal is roughly proportional to $\sqrt{(\sigma/\mu)}$. The amplitude also depends on the distance between the object and the probe l_r.

Figure 5: Measured magnetic induction reduced to a current of 1 A as function of time (symbols) and fit (lines) of a system as shown in figure 3 and table 1 put in the centre of an iron step wedge with sides of 16.5 cm and several thicknesses. a), b), c) and d) represent 4 step wedges with parameters as shown in table 3.

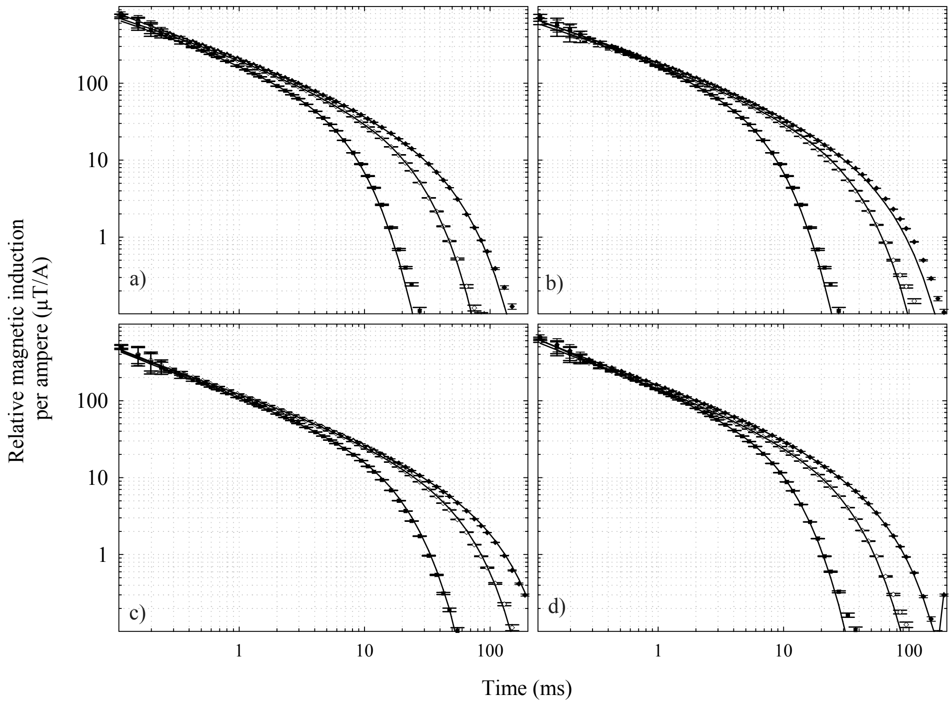
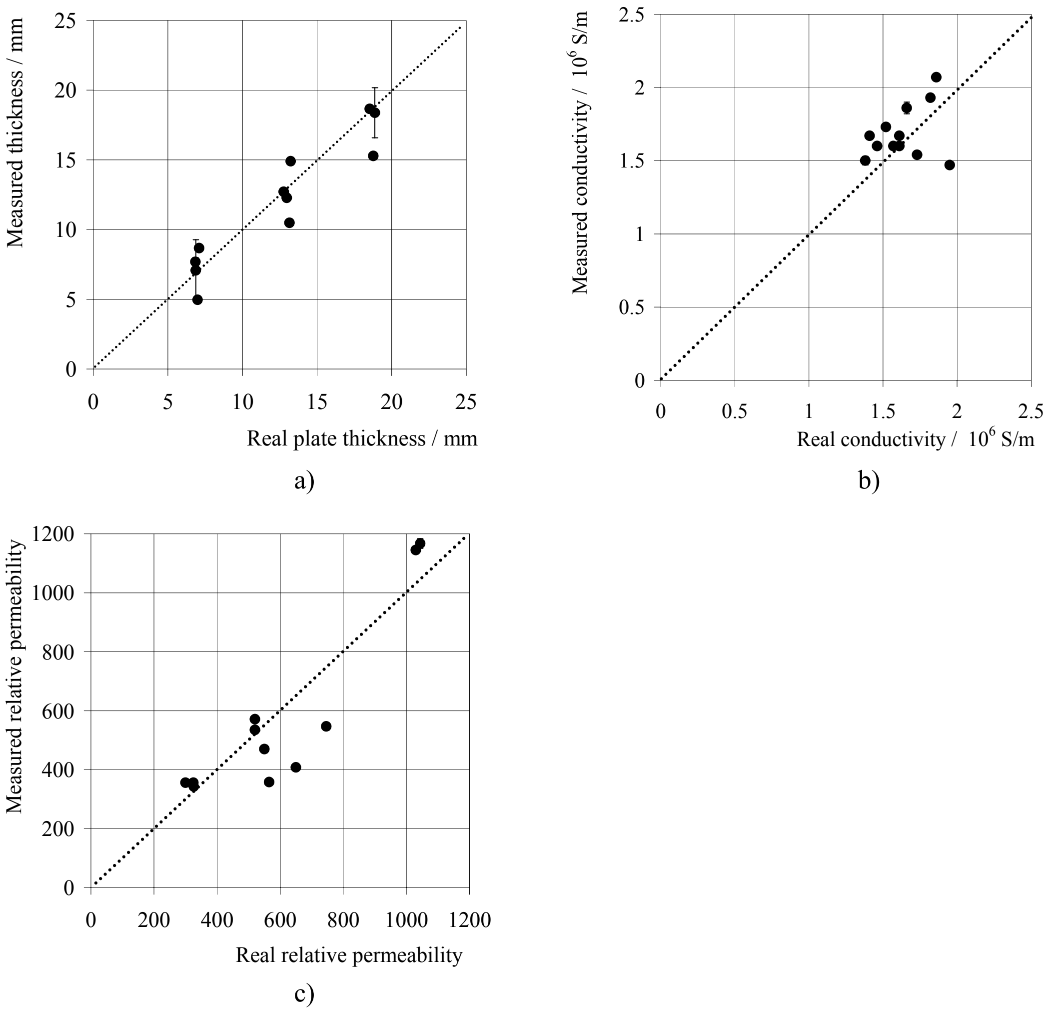


Table 3: Thicknesses and fit parameters for iron step wedges.

Step wedge	c (mm)	σ (MS/m)	μ_r	L (mm)
D2 (series a)	6.87 12.97 18.87	1.89 1.95 2.07	300 300 300	5.5 5.4 5.6
A3 (series b)	7.09 13.23 19.12	1.60 1.60 1.60	730 530 490	3.6 3.6 3.3
A4 (series c)	6.99 13.15 18.77	1.48 1.48 1.52	1000 1000 1000	4.1 4.1 4.5
D36 (series d)	6.85 12.76 18.53	1.51 1.51 1.51	530 530 556	4.5 5.1 4.1

For precise measurements this value should be accurately known. Second, it can be shown that except for the decay in the signal due to the thickness of the object, the signal also contains a decay due to the extension of the initial magnetic field created by the current through the transmitter coil. This can be derived from [2, 9].

Figure 6. Measured values determined with pulsed eddy currents without a reference measurement versus real values: a) plate thickness, b) conductivity and c) relative permeability. Dashed lines are guides for expected results.



This second decay does not depend on the thickness of the object, but it depends in the same way on the material properties as the decay due to the finite plate thickness. By fitting this decay also one can determine the material properties and hence the thickness of the object. The result of this procedure for the measurements on the carbon steel plates is given in figures 6-a, 6-b and 6-c, for the resulting thickness, conductivity and permeability respectively. Clearly one sees the relation between the measured values and the real values. One should keep in mind that no reference measurement was used to determine these values. Only the geometry of the probe and a constant l_r was used to calculate the fits. The largest deviations occur when the decays are out of the range of the measurements: too weak a signal to determine the decay for the large thicknesses or the decay of the thickness spoils the measurement of the other decay for small thicknesses. During the measurement l_r should have been constant but it is possible due to the new set-up that the position of the IGMRM sensor was changed a view tens of millimetres relative to the object influencing the results presented here.

Conclusions and development

It has been shown that it is possible to use an Improved Giant Magnetoresistance Magnetometer with the RTD-INCOTEST© system. The theoretical predictions are in full agreement with the presented measurements. More, using this system, combined measurements of material properties and object thickness are feasible. Further development will be oriented to enhance the accuracy of the method. The use of GMR-sensors opens the possibility of spatial resolution improvement by reducing transmitter coil size. More, a multi head system could be considered with a common transmitter enabling faster processing. The increase in sensitivity due to the use of GMR-sensors also opens the possibility of shaping the excitation pulse increasing the energy efficiency of the pulsed eddy current method.

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