SIMULTANEOUS MEASUREMENT OF MATERIAL PROPERTIES AND THICKNESS OF CARBON STEEL PLATES USING PULSED EDDY CURRENTS

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Abstract: It is well know from literature that Pulsed Eddy Currents generated by switching off a stationary current through a coil above a carbon steel plate can be used to measure the thickness of this plate. The procedure is to measure the induction voltage signal of a receiving coil for a known reference thickness and compare this to the signal from an unknown thickness. The disadvantage of this method is that a reference measurement is needed and the result is influenced by a change in material properties. The authors present a method using the same technique but a different signal interpretation method, enabling the simultaneous determination of material properties and thickness. A description of the signal interpretation method is given. It is shown that for several types of carbon steel an accuracy of 10% can be achieved.

Introduction: The pulsed eddy current method RTD-INCOTEST© is based on measurement of an induction voltage, $U(t)$ in a receiving coil as function of time, t . 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).

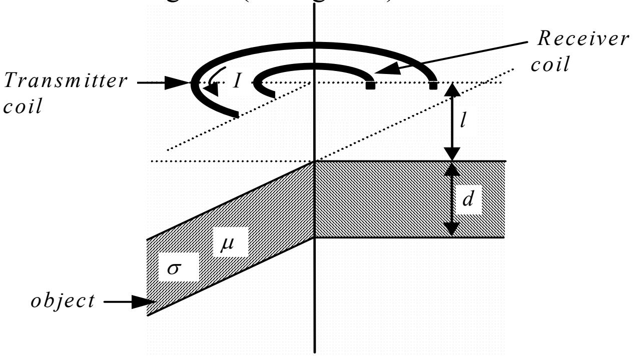


Figure 1: *Schematic set-up of RTD-INCOTEST© measurement method.*

After data processing this signal is (processed to) fit to a model with several parameters representing the material properties and thickness of the object. Typical behavior for the signal is a decay according to an inverse power law at small times and after a certain time, τ exponential decay sets in (compare figure 2, where $x=t/\tau$ and $\Theta(x)=U(x\tau)/U(0.271\tau)$). The thickness of the object can be determined by comparing the measured signal to a reference measurement of a known thickness. In most cases where RTD-INCOTEST© is applied τ is proportional to $\mu\sigma d^2$, where μ is the permeability of the object, σ the conductivity and d its thickness [1]. Hence, 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.

In certain cases this disadvantage can be overcome. Recently [2] an analytical method was developed to describe the decay of eddy currents in a circular geometry. This method facilitated the development of a more detailed model for the decay of pulsed eddy currents. The new model enables the simultaneous determination of both the material properties and the wall thickness of the object. Hence, a reference measurement is obsolete.

In the following the model is described, measurements are presented to prove the principle and limiting factors are discussed.

Results: The model is defined as:

$$U(t) = \tau^{-1.5}\Theta(t/\tau)F(\mu,\sigma,l,d,t) \quad ,$$

$$\Theta(x) = \sum_{i=1}^{\infty} i^2\pi^2 e^{-i^2\pi^2 x} \quad ,$$

where l equals the distance between probe and object. $\Theta(x)$ represents a sum over an infinite convergent series. A practical approximation is:

$$\Theta(x) = \pi^2\left(y + 4y^4 + 9y^9 + 16y^{16} + 25y^{25}\right) \text{ where } y = e^{-\pi^2 x} \quad \text{if } x \geq 0.05 \quad ,$$

$$\Theta(x) = \frac{1}{4\sqrt{\pi}x^{1.5}} \quad \text{if } x < 0.05 \quad .$$

The maximum deviation is $10^{-6}\Theta(x)$ for $x = 0.05$. Figure 2 shows $\Theta(x)$. The point at $x \approx 1/3$ is called –3 dB point as $\Theta(1/3)$ equals half of $1/(4\sqrt{\pi}x^{1.5})$.

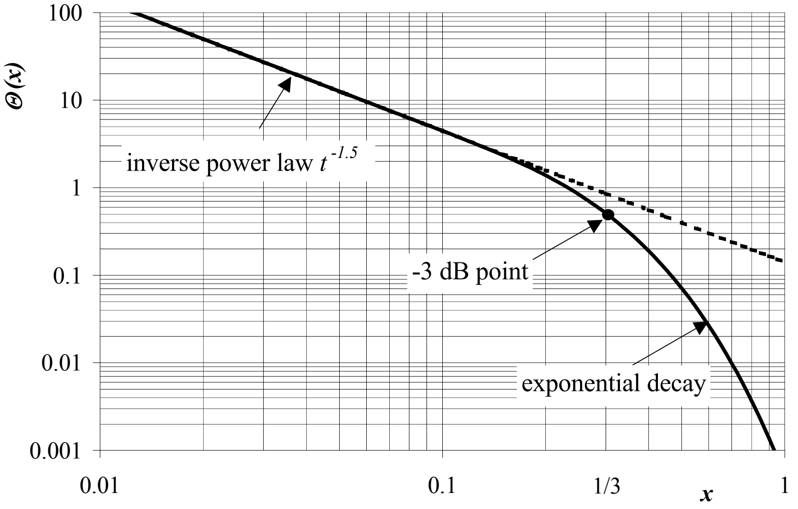


Figure 2: *Typical RTD-INCOTEST© signal response $\Theta(x)$ (full line) and -3 dB point at $x \approx 1/3$. Dashed line equals $1/(4\sqrt{\pi}x^{1.5})$. Note the logarithmic scales.*

$F(\mu,\sigma,l,d,t)$ depends on the given parameters and design of the transmitter and receiver coil. This function can be calculated using the method outlined in [2]. To be able to fit the measured data to the model, F should have a simple mathematical form. This form must enable the determination of the product $\mu\sigma$ with sufficient accuracy.

To prove the principle measurements were carried out with a transmitter-receiver system as shown in figure 3 (with dimensions given in table 1) put in the center on top of four iron step wedges.

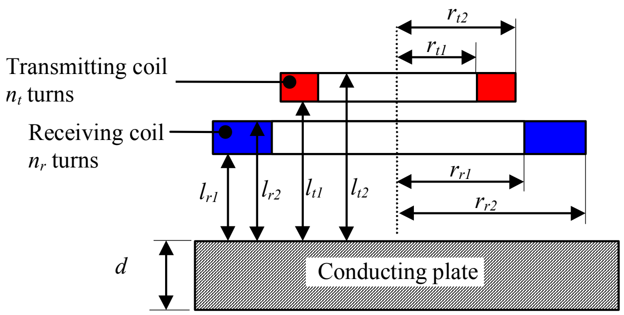


Figure 3: *Dimensions of real-live transmitting and receiving coils.*

	l_1 / mm	l_2 / mm	r_1 / mm	r_2 / mm	n
Transmitter	2.15	7.05	5.25	7.70	400
Receiver	2.15	7.05	7.70	10.25	1280

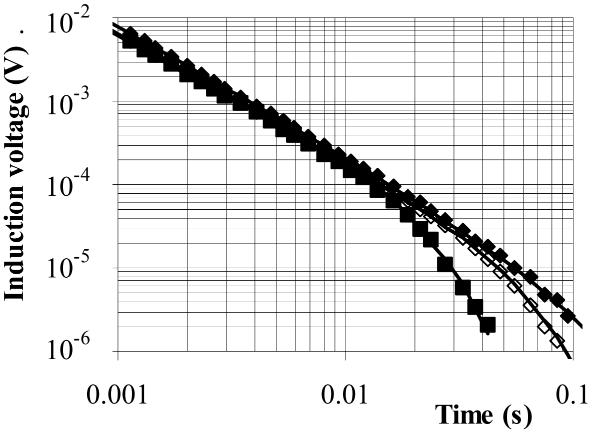
Table 1: *Dimensions of transmitter-receiver system as used in the measurements.*

All 3 steps of the wedges had a width and lengths of 16,5 cm. Measurements were performed using a system designed to measure the induction voltage of the receiver coil. An amplifier with a gain-factor of 10 and a 24-bits ADC measured the voltage. One least significant bit (LSB) was 120 nV. The sample frequency was 48 kHz. The ADC samples were averaged over a variable time-interval to obtain an accurate average and standard deviation of the measuring points. The time-interval was taken to be proportional to time. The environmental noise was suppressed by measuring the voltage for both current directions through the transmitting coil and subtracting these. The time-difference between the generation of these signals was taken a multiple of 20 ms, to obtain the maximum suppression for a noise-frequency of 50 Hz. In this way the noise for low signal levels at large times could be reduced to less than 1 LSB. The eddy currents were generated by rapidly turning off of the current of 0,60 A through the transmitter coil by using MOS-FETs (turn-off time less than 1 microsecond). The overshoot of the induction voltage was limited to 100 V by a special electronic circuit. All measurements were fitted to the model. In this case the function F is approximated by:

$$F(\mu,\sigma,l,d)=\frac{A(l,I)}{\mu}\sqrt{\mu\sigma}\left[0.91q\left(\frac{t}{\mu\sigma x_1^2},\alpha\right)+0.09q\left(\frac{t}{\mu\sigma x_2^2},\alpha\right)\right] ,$$

$$q(y,\alpha)=\frac{1}{1+y}\,\frac{y}{y+\alpha} .$$

Where α is a parameter needed to fit the start of the signal (note that the second factor in the equation for q equals 1 if $y>>\alpha$). F describes a transition between one decay region (decay proportional to power law $t^{-1.5}$) to another decay region for larger times (decay proportional to power law $t^{-2.5}$). The transition time constant is give by $\mu\sigma x_1^2$. If the measurements are accurate enough, this time constant can be measured and gives the value of $\mu\sigma$ as x_1 is known from the geometry of the system. In this case $x_1=7.6-16/d^2+45/\mu_r$ mm (d in mm and μ_r the relative permeability) and $x_2=333$ mm. The first term in the equation for x_1 is closely related to the dimensions of the transmitter and receiver coil. A, x_2 and x_1 all depend on l. Here values are used for l=0. The fitted parameters are shown in table 2. The measurements and fits are shown in figure 4. The measurement accuracy was about 1 %. The correspondence of measurements and fits is very good. No significant statistical deviation was observed. Note the difference in amplitude and bending point of the signals due to the difference in material properties.



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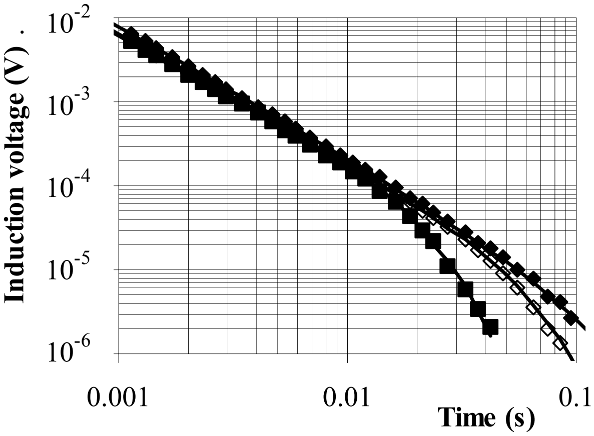

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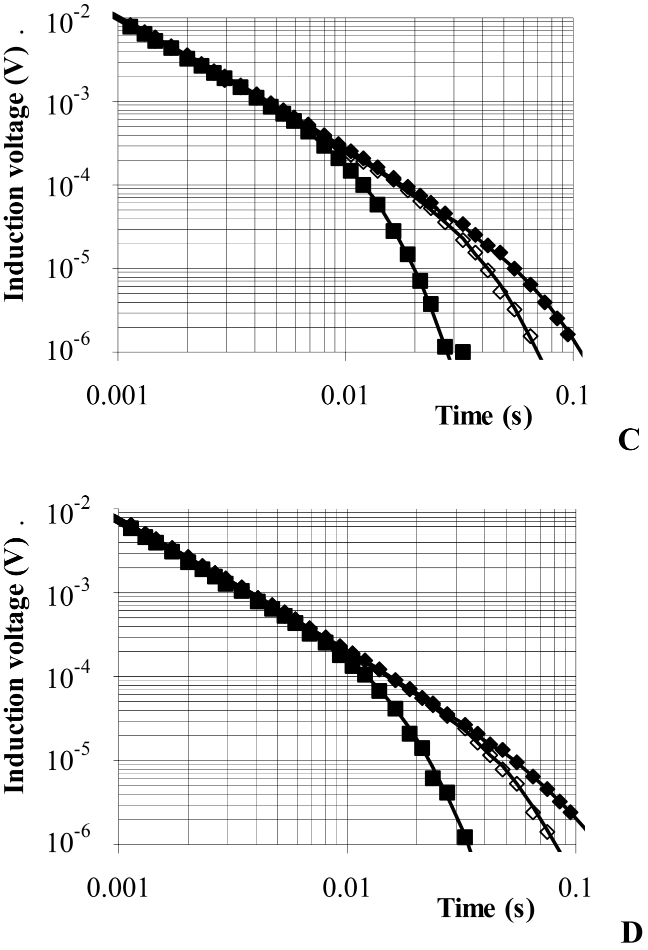

Figure 4: *Measured induction voltage (symbols) and fit (lines) of a system as shown in figure 3 and table I put in the center of an iron step wedge with sides of 16.5 cm and several thicknesses as function of time. A, B, C and D represent 4 step wedges with parameters as shown in table 2 (A4, A3, D2 and D36).*

Discussion: Table 2 shows clearly the correlation between fitted values and actual values of the desired fit parameters. The fit error is a measure for estimated accuracy of the fitted thickness. Only for the smallest thickness a deviation occurs larger than 2 mm. With the old model and a (not) favorable reference measurement the relative deviation would be at least (60) 30 %. As χ^2 varies around 1 the fit error is not determined by systematic differences but by the accuracy of the measurements. Fitted values of α varied between -10^{-4} and 10^{-4}. Theoretical α only deviates from 0 if the footprint (i.e. the extension of the applied eddy currents) is larger than the lateral size of the object. Calculations show that (in the geometry used here) 1% of the signal is generated by eddy currents at a distance larger than 7 cm from the center of the coils. The plates dimensions were 16.5 by 16.5 cm, hence the footprint was a little larger than the object. This shows the sensitivity of the method for the actual geometry of the set-up. Note that the smaller the wall thickness of the object, the less accurate the fitted wall thickness. This is due to the special form of function F and is a limitation of the method.

object	$\mu\sigma$ **ms/mm^2**	d **mm**	d_{fit} **mm**	**fit error %**	χ^2	**deviation %**	**deviation mm**
D2	0.78	18.87	19.8	6.4	0.8	5.0	0.9
		12.97	13.5	3.8	0.7	4.4	0.6
		6.87	7.5	21.0	0.2	9.3	0.6
A3	2.01	19.12	21.1	9.9	0.7	10.5	2.0
		13.23	14.1	4.6	0.8	6.2	0.8
		7.09	9.6	4.9	1.1	36.0	2.6
A4	1.32	18.77	18.9	47.0	2.4	0.9	0.2
		13.15	15.0	16.0	1.6	14.1	1.9
		6.99	10.4	9.8	0.3	48.4	3.4
D36	1.09	18.53	20.3	4.0	0.2	9.6	1.8
		12.76	13.0	4.1	0.9	2.2	0.3
		6.85	7.5	8.5	1.4	9.5	0.7

Table 2: *Fit results for 4 different objects.*

Conclusions: Simultaneous fit of two time constants from the signal measured by RTD-INCOTEST© pulsed eddy current method facilitates the determination of both material properties ($\mu\sigma$) and absolute thickness of an object. Measurements show that accurate geometry is very important. The object must be larger than the (effective) footprint and the distance between probe and object must be accurately known or measured. Accuracy of *10%* is possible and can be reduced by enhancement of probe design and measurement accuracy. Further research is needed to increase the accuracy of the method.

References:

[1] V.O. de Haan, "*Inrichting voor het bepalen van eigenschappen van een elektrisch geleidend voorwerp*", Patent number 1005160, Koninkrijk der Nederlanden, filed 31-01-1997

[2] V.O. de Haan and P.J. de Jong, "*Analytical solution and approximations of the transient induction voltage of a receiving antenna created by a transmitting antenna over a conducting plate in case of a simple cylindrical geometry*", IEEE Transactions on magnetics, to be published (submitted 10 juli 2003).