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Inductive methods Crack detection

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Abstract

In this lab we used an inductive method (using a coil) to detect cracks in metals and measure the resistivity of metals. Since there is a power loss in the metals when we induce currents to it. There should be an increased resistance in the coil which we can measure; from this the resistivity can be determined. To detect cracks we assume that the current can't flow through a crack. That means lower induced current and less power loss seen in the coil. At currents through the coil with frequency of $f = 1\ kHz$ both resistance and reactance increase in the coil near ferromagnetic materials which agrees with our theory. However at $f = 100\ kHz$ the reactance decreases. There was a noticeable change in output close to cracks. And there was also a noticeable difference in output when the coil were close to different conductors indicating that the method is well suited for measuring resistivity. However we did not find a mathematical model that fit well with the measurement.

Non-Invasive Measurement Techniques
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1 Introduction

In this experiment we will make use of electromagnetic induction to detect cracks in an electrically conductive material. In particular, we will measure the change in the (complex) voltage in a suitable probe when scanning the surface of the investigated material. We will design such a probe ourselves before starting the actual experiment. Moreover, we will determine the resistivity of a brass sample by the same method (called Eddy Current Testing).

2 Theory

2.1 Electromagnetic Induction and Eddy Currents

When supplied with an AC-voltage U_0, a coil will create an oscillating magnetic field B_L. If arranged in a closed electric circuit, a phase difference between voltage U_L and current I will occur in the coil. The correlation between voltage and current is defined as the coil impedance $Z_L := U_L/I = R_L + \mathrm{j}X_L$, where R_L characterizes the resistance of the coil and $X_L = \omega L$ its reactance. The reactance depends on the AC-frequency ω and the inductance of the coil.

When an electrically conductive material is present, the magnetic field created by the coil induces eddy currents I_c in the material. These currents cause power dissipation in the material as well as creating a secondary magnetic field B_m that opposes the primary field. Therefore, the impedance of the coil changes to $Z' = R'_L + \mathrm{j}X'_L$: its resistance increases due to the power loss while the reactance decreases with decreasing strength of the overall magnetic field.

If the investigated material is ferromagnetic, the effects described above still occur. However, the ferromagnetic material also increases the primary magnetic field, exceeding the effect of the secondary field[2]. Hence, the reactance of the coil is increased instead of being lowered (see figure1).

2.2 Crack Detection

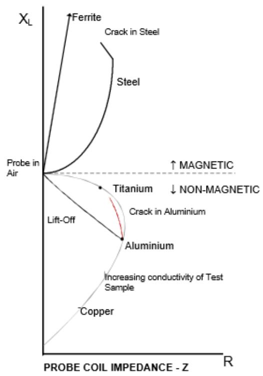

Figure 1: the impedance Z of the probe as a function of scanned material[1]

When cracks are present in the material (at the position of the probe), they impede the flow of eddy currents, thus decreasing the power dissipation and the strength of the secondary magnetic field. As a consequence, the coil's resistance changes to R''_L (where $R_L < R''_L < R'_L$) and its reactance changes to X''_L (where $X_L > X''_L > X'_L$ for non-ferromagnetic materials and $X''_L > X'_L > X_L$ for ferromagnetic materials respectively) as seen in figure1.

2.3 Calculation of resistivity

From electromagnetic theory we have that the induced current density J at a given depth d from an external field in a conductor is given by

$$\mathbf{J} = \mathbf{J_s} e^{-d/\delta} \tag{1}$$

where Js is the current density at surface of the metal and δ is the skin depth given by

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} \tag{2}$$

where ω is the angular frequency of the current, μ is magnetic permeability and ρ is the resistivity. Furthermore the electric field in a conductor is given by

$$\mathbf{E} = \rho\mathbf{J}. \tag{3}$$

Using eq. (1), (2) and (3) together with the equation for Joule heating we get

$$P_{loss}(d) = \mathbf{E} \cdot \mathbf{J} = \frac{1}{\rho} E^2. \tag{4}$$

From eq. (1) and (3) we have that $\mathbf{E} \propto e^{-d/\delta}$ and so

$$P_{loss}(d) \propto \frac{1}{\rho} e^{-2d/\delta}, \tag{5}$$

to get the total power loss P_c we integrate over the thickness of the metal

$$P_c = \int_0^D P_{loss}(d) \approx \int_0^\infty P_{loss}(d) = \frac{C'}{\rho} \int_0^\infty e^{-2d/\delta} = \frac{C}{\rho}\delta \tag{6}$$

where C' and C'' are some constants; we can calculate the integral over infinite depth as long as the thickness D of the metal is much larger than δ. Holding everything but ρ fixed and using eq. 2 we get that

$$P_c = C\sqrt{\rho} \tag{7}$$

where C is some constant.

This power loss due to heating in the conductor equivalently mean increased resistance in the source of the external field, from Ohm's law

$$P_{ohm} = \Re(\Delta U_L)I \tag{8}$$

where ΔU_L is the change in the real part of the voltage and I is the current of the external field source which is defined as without phase. Since $P_{ohm} = P_c$ we finally get that

$$\Re(\Delta U_L)I = C\sqrt{\rho}. \tag{9}$$

assume I_s is constant and this simplifies to

$$\rho = \left(\frac{\Re(\Delta U_L)}{C}\right)^2 \tag{10}$$

for some other constant C.

3 Experimental

All measurements take place at room temperature.

3.1 Set up

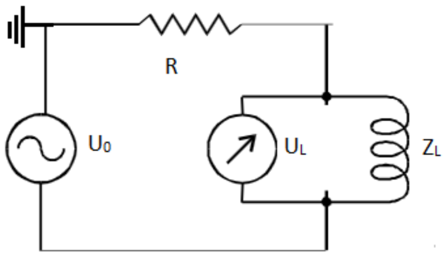

Figure 2: schematic of the electric circuit used in the experiment[1]

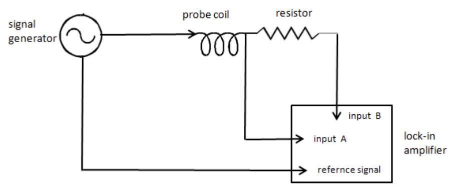

Figure 3: schematic of the set up of the electric equipment

First, we built a probe coil with impedance Z_L by spooling a copper wire on a ferrite core. Then, we connected this coil together with a resistor $R = 1\ \text{k}\Omega$ to a signal generator that provides a complex voltage $V_0 = 0.1\ \text{V} \cdot e^{2\pi j f}$ as shown in schematic 2, and 3. A 2-input lock-in voltmeter is used to measure the voltage over the resistor as well as the voltage over probe and resistor combined. This allows us to measure the voltage U_L over the probe, too, since the voltmeter can calculate the difference between its two input signals. The probe coil can be moved manually to scan sample surfaces.

3.2 Crack Detection

For the crack detection test, we put the coil on the surface of a sample in such a way that the coil's magnetic field enters the sample perpendicular to the surface. We measured the coil voltage U_L at different positions of the probe relative to a visible crack in the sample. In addition, we took a reference measurement for the coil voltage in air. Such a set of measurements was taken for three different AC-frequencies ($f = 1$ kHz, $f = 20.9$ kHz, and $f = 100$ kHz).

3.3 Resistivity Measurement

For the resistivity measurement, we put the coil on samples of different materials with known resistivity (copper, aluminium, tin, and lead) and measured the coil voltage U_L. The supplying AC-voltage had a frequency of 20.9 kHz We took a reference measurement with the coil in air, as well. This data is used to calibrate our probe. Afterwards we measured the coil voltage while probing a brass sample of unknown resistivity. From that, we try to calculate the resistivity of the brass sample.

4 Results

4.1 Crack Detection

		$\lvert U_L\rvert$ [mv]	ϕ [°]	Re(U_L) [mV]	Im(U_L) [mV]
$f = 1$ kHz	in air	1.69	80.48	0.28	1.67
	on crack	2.85	76.60	0.66	2.77
	edge of crack	2.79	75.93	0.68	2.71
	1 cm from crack	2.65	74.38	0.71	2.55
	2 cm from crack	2.64	74.37	0.71	2.54
$f = 20.9$ kHz	in air	32.84	90.03	-0.02	32.84
	on crack	38.03	78.46	7.61	37.26
	edge of crack	36.48	79.64	6.56	35.89
	1 cm from crack	34.47	80.50	5.69	34.00
	2 cm from crack	34.06	80.73	5.49	33.62
$f = 100$ kHz	in air	98.74	63.76	43.66	88.56
	on crack	98.61	63.53	43.95	88.27
	edge of crack	98.56	63.51	43.96	88.21
	1 cm from crack	98.47	63.50	43.94	88.12
	2 cm from crack	98.46	63.50	43.93	88.12

Table 1: The measured complex coil voltage $U_L = |U_L| \exp(j\omega\phi) = \mathrm{Re}(U_L) + \mathrm{jIm}(U_L)$ depending on the the position of the coil and the frequency f of the supply voltage

In order to test the ability to detect cracks in a material, we moved the probe to different positions on the surface of a material with a visible crack. Then we measured the coil voltage at those points as well as for the coil in air. Since we measured a constant current in the coil over the entire experiment, the voltage is directly proportional to the impedance of the coil. As shown in figure 4, 5, and 6, the impedance changes abruptly in the vicinity of a crack. Therefore, we are indeed able to detect cracks in an electrically conductive material.

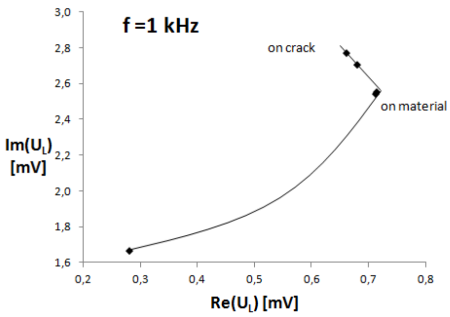

Figure 4: change in the coil voltage U_L as a function of the position of the probe at a frequency $f = 1$ kHz

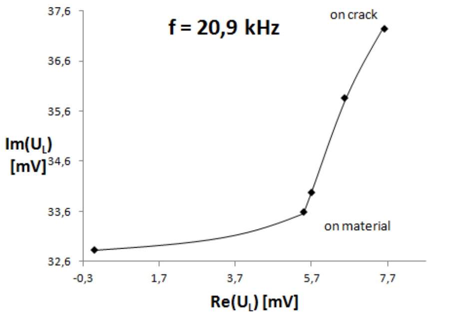

Figure 5: change in the coil voltage U_L as a function of the position of the probe at a frequency $f = 20.9$ kHz

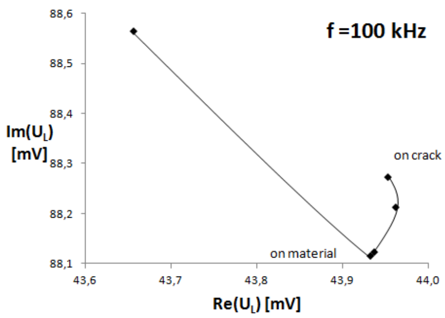

Figure 6: change in the coil voltage U_L as a function of the position of the probe at a frequency $f = 100$ kHz

4.2 Results of resistivity measurement

In our experiment the change $\Re(\Delta U_L)$ could be measured using the lock-in amplifier. In order to calculate the constant C in eq. (10) we did measurements in three metals with known resistivity: copper, aluminium and tin. At the measured frequency the skin depth, see eq. (2), would be around 1 mm for $\rho = 10^-7$; and the measured conductors were much thicker than this, in the order of one centimetre. So no consideration were taken into the geometry of the conductor. The measurements along with resistivity and evaluated constant C can be seen below in table 2.

Table 2: Measurements of known metals to evaluate C.

metal	$\Re(\Delta U_L)$ (mV)	ρ (Ωm)	C
Copper	1.56	1.68E-8	12036
Aluminium	1.50	2.82E-8	8932
Tin	0.83	1.15E-7	2448

The reader can see that the measured value for the constant C differs by almost a factor of six between copper and tin; also it is higher for metals with lower resistivity among the metals measured.

The average of these values for C minimizes the summed square error and gives that $C = 7805$ This value for C and a measured change in voltage $\Re(\Delta U_L) = 1.22mV$ for an unknown composition of brass gives $\rho = 2.4432E - 8$ compared to brass with 58% and 63% copper which have resistivity $5.9E - 8$ Ωm and $7.1E - 8$ Ωm respectively.

5 Discussion

5.1 Crack Detection

At the lower frequency of $f = 1$ kHz, our results (see fig.4) agree with the theoretical expectations for ferromagnetic materials (see fig.1): both resistance and reactance of the coil rise in the presence of the material. At a crack, the reactance continues to rise, while the resistance decreases.

However, at higher frequencies the resistance at a crack rises as well, suggesting a power dissipation due to the crack.

At a frequency $f = 100$ kHz, the reactance decreases when the probe coil is situated on the material. This indicates that the material is then non-ferromagnetic. A possible reason for this behaviour might lie in the small penetration depth of the magnetic field into the material at a high frequency. Here, the magnetic permeability μ of the material is reduced to almost unity[3], inhibiting the increase in strength of the primary magnetic field.

5.2 Resistivity Measurement

We think the results were poor because the theory did not fit well with reality. We don't think the deviation to the constant in table 2 is due to any measurement error since the set up used could measure in nano-volts; also the values in table 2 for the constant C was higher for lower resistivity, so it followed a pattern which it should not. We are not sure about the dependence of ρ on the *assumed constant* J_s in eq. (1); intuitively we assumed that it might be proportional to $1/\rho$, but that will still fit reality even worse. However there is differences in the measured values for the voltages for different materials with different resistivity so this indicates this method can be used to measure resistivity.

6 Conclusions

6.1 Crack Detection

With our set up, we are able to detect cracks in an electrically conductive material, as was the main goal of the experiment. At higher frequencies ($f > 20$ kHz), the behaviour of the probe impedance deviates from theoretical considerations for ferromagnetic materials. While the deviation of the reactance can be interpreted by the sample loosing its ferromagnetic properties, the anomaly of the resistance could not be satisfyingly explained.

6.2 Resistivity Measurement

With this set up we believe that you can make accurate measurements of resistivity. A better model is needed and we think this can be derived from [4].

References

[1] An introduction to Eddy Current Testing, Jospeh M. Buckley, `http://joe.buckley.net/papers/eddyc.pdf`(2013/Dec/06)

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