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A portable embedded contactless system for the measurement of metallic material conductivity and lift-off

Nuno M. Rodrigues [a], Luis S. Rosado [b], Pedro M. Ramos [a,*]

[a] Instituto de Telecomunicações, Instituto Superior Técnico, Universidade de Lisboa, Portugal
[b] Instituto Superior Técnico, Universidade de Lisboa, Portugal

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A B S T R A C T

This paper describes the development, implementation and characterization of a portable embedded measurement system for the contactless estimation of a metallic material conductivity and of the lift-off between the system probe and the metallic material surface. The system consists on an absolute probe with compensation and is capable of measuring the in-phase and in-quadrature components of the probe output voltage using as a reference the probe stimulus voltage. The stimulus module includes a direct digital synthesizer (DDS) to set the measurement frequency, while the acquisition module includes analog voltage amplification and analog-to-digital conversion. A microcontroller is used to control the measurement, process the acquired voltage samples, estimate the desired parameters and perform USB communication. The final dimensions of the pen-like system, its capability of communication with a smartphone and its ability to power the system from the smartphone make it highly portable and especially suited for non-destructive testing (NDT) and field measurements.

1. Introduction

Non-Destructive Testing (NDT) has become one of the most relevant technologies in the maintenance of many industrial fields [1–3]. The assessment of the capability of a part without damaging it, constitutes a major advance in maintenance operations. In addition, if the part can be tested in its operation location without the need to disassemble it from the system, even further advantages can be obtained both in testing speed and reduction of system maintenance downtime.

There are different NDT technologies that can be used and their suitability depends on each specific application. These include among others [3]: liquid penetrant inspection; magnetic particle inspection; electrical test methods; ultrasonic testing; radiography; optical inspection and thermography. Specifically, for metallic parts, Eddy Currents Testing (ECT) is one of the most used techniques. An excitation module generates a magnetic field that creates eddy currents in the testing part. These will generate another magnetic field and the resulting magnetic field depends on the material under test, its imperfections and on the distance between the generation module and the metallic part (typically called lift-off).

Within ECT, multiple probe designs have been proposed. The most basic design includes a single coil with multiple windings. An alternate current in the coil generates the magnetic field that will interact with the part under test. The assessment of the part characteristics/defects is obtained by the measurement of the coil impedance [4,5]. However, this approach requires a very good impedance measurement accuracy/resolution since any changes in the impedance value are always sensed as changes from the nominal coil impedance. To improve measurement accuracy and resolution, a compensation coil can be used [6]. This coil is identical to the excitation coil but is located away from the test material and each coil is part of a bridge arm. With this setup, measurement accuracy and sensitivity is improved even if the compensation is done for the excitation coil without any material in the proximity. Another approach to circumvent the single coil shortcomings is to separate the excitation and sensing probe stages. This enables a variety of configurations as can be seen for example in [7–9]. Specifically, in [7], the excitation stage is a single wire with the sensing coils located on each side in the same plane. This approach enables, as desired, the separation between the field excitation and sensing stages and also a differential measurement setup ideally suitable for defect detection and with lift-off immunity. In fact, when the material underneath the probe has no defects, the field

* Corresponding author.
E-mail addresses: nuno.medeiros.rodrigues@tecnico.ulisboa.pt (N.M. Rodrigues), luis.rosado@tecnico.ulisboa.pt (L.S. Rosado), pedro.m.ramos@tecnico.ulisboa.pt (P.M. Ramos).

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sensed in both coils is identical and the resulting measurement is null. In the presence of lift-off, the field measured by each coil is similarly affected and the probe output is also null.

To detect defects in large parts, a mechanical probe positioning system should be used. However, to improve the resolution of the defect location estimation, the probe should be as small as possible and thus scanning of large areas can require a significant amount of time. One possible workaround for this problem is the use of sensor arrays as proposed in [10] which can, for each probe position, scan a larger area without compromising location resolution.

Defect detection at different depths requires different measurement/excitation frequencies [6]. This means that different testing frequencies enable the assessment of the part at different depths. One possible method that does not significantly increase the testing duration is to simultaneously excite multiple frequencies and measure also at those frequencies. Pulsed Eddy Current (PEC) is a simple commonly used method to generate (and stimulate) multiple frequencies [10–15].

Measurements at frequencies above 100 kHz require special care due to cable inductances, the need for high-speed analog-to-digital converters and fast signal processing microcontrollers/processors [16]. One solution to perform these measurements without the need for high-performance components is to execute the in-phase and in-quadrature (IQ) demodulation in the analog domain as used for example in [17,18].

In addition to detection and characterization of defects, NDT techniques can be used for material identification from their conductivity. It has been shown for example in [2,6,19] that the coil impedance depends on the material conductivity and on the lift-off between the coil and the material under test. Commercial devices that perform these measurements are, however, quite bulky and expensive [20]. Even medium or large companies usually only have one device of this type and whenever they malfunction, they must be returned to the manufacturer leaving the company without the measurement equipment. To address this issue, this paper describes the development, implementation and characterization of a portable conductivity/lift-off contactless measurement system capable of field operation in a pen-like casing with the aid of an Android smartphone. The modular approach, and the resulting lower cost, can enable a company to have multiple devices and use generic smartphones to display and record the measurements. The system is based on an absolute probe with compensation and software based IQ demodulation. The use of a digital signal processor to execute the IQ demodulation stage, taking advantage of the synchronous operation between the signal generation and signal acquisition stages is a significant novelty. With this approach, only one analog to digital converter is required and no analog multipliers are used. In the end, this is used to reduce system power consumption and its overall size.

2. Single coil eddy currents sensor

In a single coil eddy currents sensor, an alternating current in the coil generates a magnetic field that induces the eddy currents in the target material. These, in turn, create an opposing magnetic field, which interacts with the field generated by the probe coil [19]. The resulting magnetic field is dependent on the distance between the probe and the target material and also on the material composition. This change in the magnetic field is reflected in the coil impedance which can be measured for example with an impedance analyser. The use of a ferrite in the coil can increase the coil inductance, increase the quality factor of the coil and improve the probe sensitivity [11]. Fig. 1 shows a graphical representation of the eddy currents and magnetic fields.

If the distance between the coil and the material changes, the impedance measurement system senses it as a variation in the coil impedance [1–2,4,6] and the same occurs when the material under test is altered. These effects enable identification of different materials and measure different lift-offs. Lift-off variations can be caused by varying non-metallic coating thickness, irregular sample surfaces or the operator's movement [12].

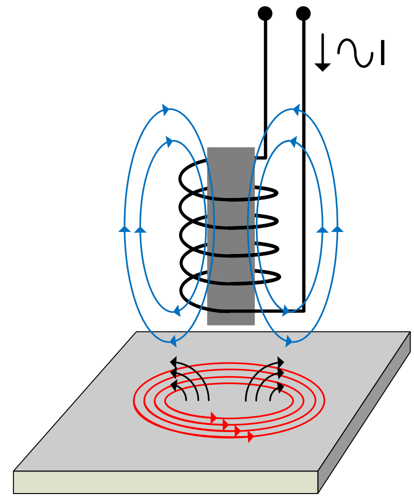

Fig. 1. Graphical representation of the eddy currents and magnetic fields. The rectangular shape inside the coil is the ferrite.

Eddy current based systems for use in displacement measurement and metrology applications [21] use complex electronic designs for driving the probes and measuring their outputs. These high-performance systems have outputs which are very linear, stable with temperature and able to detect small changes in target position.

In [2], relations are presented to estimate the real and imaginary part of a single coil impedance as a function of the material conductivity and lift-off between the coil and the material. Results obtained with a 2 mm diameter and 1 mm length coil for a frequency of 60 kHz are shown in Fig. 2. The different samples correspond to the materials tested in the experimental validation (identified by their conductivity expressed in %IACS – International Annealed Copper Standard) and the evolution corresponds to

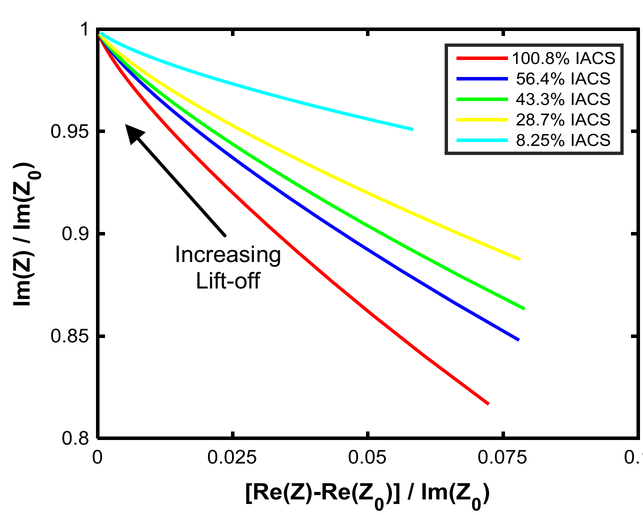

Fig. 2. Theoretical result of variations of $Im(Z)/Im(Z_0)$ (normalized coil impedance imaginary component) and $[Re(Z) - Re(Z_0)]/Im(Z_0)$ (normalized coil impedance real component) from the 'infinite' lift-off position that corresponds to $Im(Z)/Im(Z_0) = 1$ (no change in the imaginary part) and $[Re(Z) - Re(Z_0)]/Im(Z_0) = 0$ (no change in the real component).