Sensors and Actuators A 173 (2012) 17–23

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Contactless hybrid sensor for simultaneous detection of light reflectance and eddy currents

L.E. Helseth [a,b,*]

[a] Department of Physics and Technology, University of Bergen, N-5007 Bergen, Norway
[b] The Michelsen Centre for Industrial Measurement Science and Technology, Bergen, Norway

ARTICLE INFO

Article history:
Received 18 April 2011
Received in revised form
29 September 2011
Accepted 1 October 2011
Available online 18 October 2011

Keywords:
Light reflectance
Eddy currents
Resonance
Frequency spectrum

ABSTRACT

We demonstrate a contactless hybrid sensor for the simultaneous detection of light reflectance and eddy currents. The sensor is based on combining an optical system with an RLC self-resonator, wherein the reflected light intensity and resonance frequency are measured. We demonstrate that the hybrid sensor can be used for monitoring metals coated with non-metallic films. Whereas the self-resonator can efficiently distinguish between metals and non-metals, the optical subsystem is sensitive to changes in the reflectance of light. A systematic investigation of the detector response as a function of distance to the material under test is undertaken to characterize its behavior.

1. Introduction

Non-destructive testing and evaluation of metallic materials or compositions often rely on eddy current sensors [1–5]. For example, inductive techniques have been shown to allow determination of the diameter of metal powder particles, thus providing an alternative to light-scattering techniques [6]. Eddy current sensors are particularly useful for monitoring moving parts composed of metals or conducting fluids [2,7]. It has also been found that inductive pulse sensors based on planar coils may effectively monitor oil debris in the form of microscopic metallic particles [8]. When it comes to planar metal surfaces, studies the last 20 years have demonstrated scanning-based imaging of defects, flexible proximity testing, fluid displacement sensors as well as efficient extraction of thickness and conductivity of metallic layers using eddy current techniques [4,9–11]. Furthermore, differential probes have been developed to suppress noise and improve the sensitivity and robustness [12]. However, detection of dielectric coatings on top of metals remains a difficult task using this technique due to the fact that such coatings are largely non-conducting and cannot be easily distinguished from the surrounding air.

With the push towards increased functionality, there is a need to develop more complex sensors systems combining two or more detection principles. Recently, a novel hybrid sensor utilizing a combination of optical reflection and capacitance measurements was reported by Kimoto et al. [13,14]. This sensor showed remarkable sensitivity towards a range of materials parameters and had the capability to detect and monitor a range of metallic and nonmetallic materials within a small volume. However, in rough (humid) environments capacitive detection may not always be optimal since it relies on a well-defined charge on the sensor, which under certain settings may be influenced by the surroundings.

Thus, it may advantageous to also consider other detection schemes. To this end, it is useful to note that optical detection schemes are very robust, as are properly shielded eddy current sensors. In a number of recent studies it has been demonstrated that eddy current sensors utilizing resonance circuits are particularly sensitive [15–19]. Woodard and Taylor demonstrated that small changes in the resonance of an oscillating LC circuit occur due to changes in the surrounding medium, and used this principle to create fluid level sensors [15,16]. Wang et al. demonstrated a highly sensitive cryogenic position sensor based on an inductor coupled to a frequency-modulated oscillator [17]. Riistama et al. reported the use of LC resonators for monitoring bioimpedance potentials, aimed at monitoring the heart rate in human beings [18]. Robaina et al. reported a new type of differential resonator able to monitor metals as well as glucose in blood [19]. These studies represent important steps towards using such sensors also for detecting non-metallic objects.

An alternative method for monitoring dielectric coatings on top of metals is by combining two principles into one sensor,

* Correspondence address: Department of Physics and Technology, University of Bergen, N-5007 Bergen, Norway
E-mail address: Lars.Helseth@ift.uib.no

0924-4247/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2011.10.002

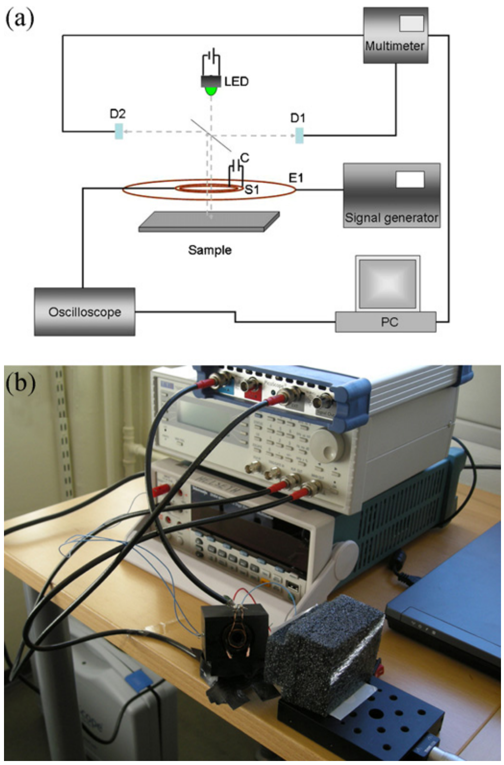

Fig. 1. A schematic drawing of the setup used in this study (a) and picture of the complete setup (b). Here E1 is the excitation coil, S1 is the resonator coil, C is the capacitor, D1 is the reference photodiode and D2 is the main photodiode for detecting the reflected optical signal. In the image of the complete setup, the sensor has been rotated towards the camera and the black plastic film covering the coils has been removed such that one can see the entry points of these coils.

inspired by the work of Kimoto et al. [13,14]. Here we demonstrate a hybrid sensor using optical reflection combined with a novel resonance pulsed eddy current detection scheme in order to distinguish coated and noncoated metals. Separately, these two techniques are not able to provide reliable and contactless detection of such specimens. For example, while the optical sensor is able to distinguish between metals covered with different coatings, this situation changes once all the metals have the same coating. On the other hand, an eddy current sensor easily distinguishes between metals of different conductivities and magnetic properties, but cannot reliably provide information about the presence of a thin non-metallic coating. In this work we demonstrate a contactless sensor combining these two principles, and characterize its properties.

2. Methods

The sensor described here combines two principles, one based on reflection of light and another based on monitoring eddy currents, see Fig. 1. In the following we will describe the associated working mechanisms.

2.1. Optical sensor

The optical sensor utilizes a simple design with a light emitting diode (LED) emitting nearly monochromatic light, which is reflected from the sample, see Fig. 2a. The light emitted by the LED is unpolarized and nearly collimated by an aperture placed in front of it. After being reflected by the sample, the light propagates back into the sensor volume where it is deflected at the beamsplitter (of reflectance coefficient R_B) before it finally enters a photodiode (D2). Note also that the light beam from the LED is reflected by the same beamsplitter to a different photodiode (D1) before propagating towards the sample. The purpose of this photodiode (D1) is to ensure that the intensity emitted by the LED is stable, and that possible variations can be accounted for, if necessary.

The reflectance coefficient $R_L(\lambda)$ of the sample depends on several factors, including its refractive index and surface roughness. A perfectly planar sample of refractive index $n(\lambda)$, where λ is the wavelength of the light, has a reflectance coefficient given by

$$R_L(\lambda) = \left[\frac{n(\lambda)-1}{n(\lambda)+1}\right]^2, \quad (1)$$

where the surrounding air has refractive index 1. In the case of a specularly reflecting sample fulfilling Eq. (1), we can find the power incident on the detector by considering the unfolded beam path of Fig. 2b. This unfolded beam path does not represent the real geometry, but is useful for considering the light propagation in the case of specular reflection. We observe that the light emitted from the LED travels a fixed length $L = L_1 + L_2$ inside the hybrid detector and a distance $2d$ outside it. The limiting aperture is in this case the photodiode D2 of radius r. The light emitted from the photodiode has an angular spread θ, such that in absence of any aperture the beam would have a radius $R = (L + 2d)\tan\theta$ at the position of the photodiode. The power reaching the photodiode is then given by $P = R_L(\lambda)R_BP_0\pi r^2/\pi R^2$, where P_0 is the power of the LED light beam at $d = 0$ in absence of the sample. The signal (in V) read by the multimeter of Fig. 1 is proportional to the incident power, $U = \eta P$ (η, which has units V/W, is a conversion factor), such that

$$U = \frac{P_1}{(L+2d)^2}, \quad P_1 = \eta R_L(\lambda) R_B P_0 \left(\frac{r}{\tan\theta}\right)^2. \quad (2)$$

For diffusively scattering samples, the expression for the reflection coefficient R_L is more complex due to the fact that most materials with roughness larger than the wavelength exhibit both specular and diffuse reflection. In Fig. 2a, the light is impinging on a diffusely reflecting sample, and most of the scattered light does not enter the detector. In fact, only light within a narrow cone centered on the optical axis is allowed to reach detector D2. The cone angle decreases with distance between the sample and the detector, but often in a nontrivial manner. It is outside the scope of this work to model reflectance from partially diffusely scattering samples.

2.2. Eddy current sensor

A simplified equivalent circuit diagram of the eddy current sensor in absence of the sample is shown in Fig. 3. A resonating RLC circuit is set into self-oscillations by a very short, pulsed magnetic field using an excitation coil of resistance R_2 and inductance L_2. The RLC circuit is build up of a capacitor of capacitance C and a coil of self-inductance L_1. The resistance R_1 in the equivalent circuit is due to the finite resistivity of the coil. The coupling of the two circuits is represented by a mutual inductance M.

The two coupled circuits of Fig. 3 can be analyzed using Kirchoff's law, which allows us to find the currents i_1 and i_2 over the two circuits from the following coupled differential equations:

$$L_1\frac{d^2 i_1}{dt^2} + R_1\frac{di_1}{dt} + \frac{i_1}{C} + M\frac{d^2 i_2}{dt^2} = 0, \quad (3)$$

and

$$L_2\frac{d^2 i_2}{dt^2} + R_2\frac{di_2}{dt} + M\frac{d^2 i_1}{dt^2} = 0. \quad (4)$$

In the following we will neglect the resistance R_2, since including it does not significantly influence the physics of interest here (i.e. the existence of decayed oscillations). If one assumes that the current