Accurate measurement of Aluminum layer thickness in a multilayer material using eddy current sensor

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Abstract—**This paper presents an eddy current sensor based system that allows thickness measurement of an Aluminum layer in multilayer material. An electromagnetic analytical model is used to give the relationship between the response of the eddy current sensor and the Aluminum layer thickness for different frequencies, and then looking for the optimal working frequency according to a given criterion. The measurement system is performed and controlled by a Labview application in which the analytical relationship is integrated. Some experimental samples of multilayer material containing an Aluminum layer with different thicknesses are used to verify the measurement system. A good accuracy and agreement is observed between the measured thicknesses and the exact thickness of the samples.**

Keywords— **EC-NDE; EC sensor; Thickness measurement; conductive coating; multilayer material.**

I. INTRODUCTION

Different protective coatings or surface treatments are used to improve the behaviour of steel. This coating acts as a physical barrier which isolates the steel from the exterior environment. Unprotected steel is used only in a dry environment and not corrosive, therefore to use the steel outside this environment various solutions such as Aluminium metallic coating can be used [1-4]. Thickness measurement and controlling of the Aluminium coating are necessary for the steel fabrication. As well, in the manufacture and maintenance of industrial metal pieces, it is very important to make the control and the measurement of their geometrical properties [5]. Eddy current based methods which are widely used in non-destructive testing of conductive materials [6]; can be also used as an alternative method for thickness measurement [7-10]. The main advantages of eddy current methods are the low cost and the robustness [11-13]. According to the penetration depth equation, we can understand that the penetration of eddy current in the material is relative to geometrical, electric and magnetic proprieties and the working frequency as:

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \qquad (1)$$

δ is the depth of penetration, f is the eddy current frequency, μ is the magnetic permeability and σ is the electric conductivity of the material.

On the other hand, in real conditions, there are a lot of parameters that affect the eddy current distribution in the material under test such as the eddy current sensor dimensions, material thickness, and the gap between the sensor and the material so-called lift-off [5]. If one or more of these parameters change, the response of the eddy current sensor changes. By using an appropriate processing of the sensor response a lot of material properties can be evaluated such as its thickness. Labview program is a very comfortable and a simply design environment for the data acquisition, processing and visualisation [14, 15]. In this paper an eddy current sensor based system that allows thickness measurement of an Aluminium layer in multilayer steel material is performed. For that, the relationship between the eddy current sensor response and the Aluminium layer thickness is given by the electromagnetic analytical model of Dodd and Deeds [16, 17]. The measurement setup is controlled by a Labview application in which the given relationship is integrated. A series of multilayer material containing Aluminium layer with different thicknesses ranging from 0.03 mm to 0.18 mm are prepared as experimental samples and then measured.

II. ELECTROMAGNETIC ANALYTICAL MODEL

The corresponding problem (Fig. 1) is an eddy current sensor placed above the material made of two layers; the first one is an Aluminium layer while the second one is a steel layer. The EC sensor is made with 407 turns, with outer diameter (D_o) of 19.4 mm, inner diameter (D_i) of 10 mm, height (h) of 4 mm. The lift-off is about 0.1 mm. Table I show the geometrical and physical proprieties of the material.
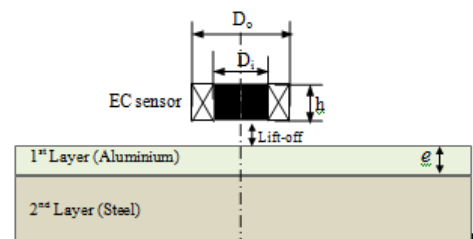

Fig. 1. Problem description

TABLE I.   PHYSICAL AND GEOMETRICAL PROPRIETIES OF MATERIAL.

Layer	Electric conductivity [MS/m]	Relative magnetic permeability	Thickness [mm]
1st Layer (Aluminium)	35.5	1	From 0.03 to 0.18
2nd layer (steel)	4.2	50	5

The electromagnetic analytical solution of the corresponding problem is given by Dodd and Deeds formulation. The normalized resistance and reactance of the sensor given by equations (2) and (3) are calculated for various Aluminium layer thicknesses and different frequencies (Fig. 2).

$$X_n = \frac{X_c}{X_0} \qquad (2)$$

$$R_n = \frac{R_c - R_0}{X_0} \qquad (3)$$

R_n and X_n are respectively the normalized resistance and normalized reactance .R_c and X_c are respectively the resistance and reactance of the eddy current sensor.X_0 is the sensor reactance deprived of the material.
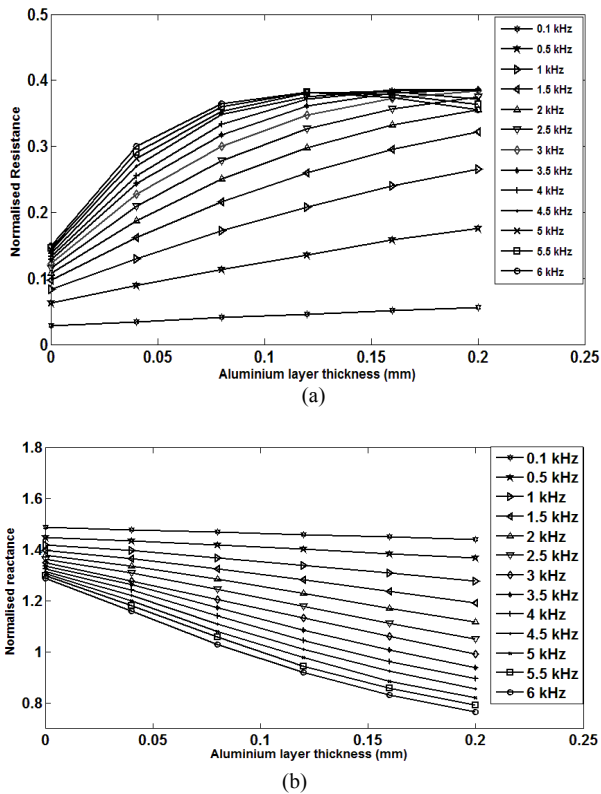

Fig. 2. Normalized resistance and reactance of the eddy current sensor
(a) normalized resistance, (b) normalized reactance.

The purpose here is to find the optimal working frequency f_0 that satisfy the following two criterion; a good sensitivity of the sensor and a best linear relationship between R_n or X_n and the Aluminum layer thickness. Accordingly, we calculate both resistance and reactance sensitivities which are given by the ratio between the reactance or resistance differences of two successive calculations and the difference of the corresponding Aluminum layer thicknesses as:

$$S = \frac{\Delta G_n}{\Delta e} \qquad (4)$$

G_n can be the normalized resistance R_n or the normalized reactance X_n and e is the Aluminium layer thickness. The resistance and reactance sensitivities vs. the Aluminium layer thickness for different frequencies are shown in Fig. 3.
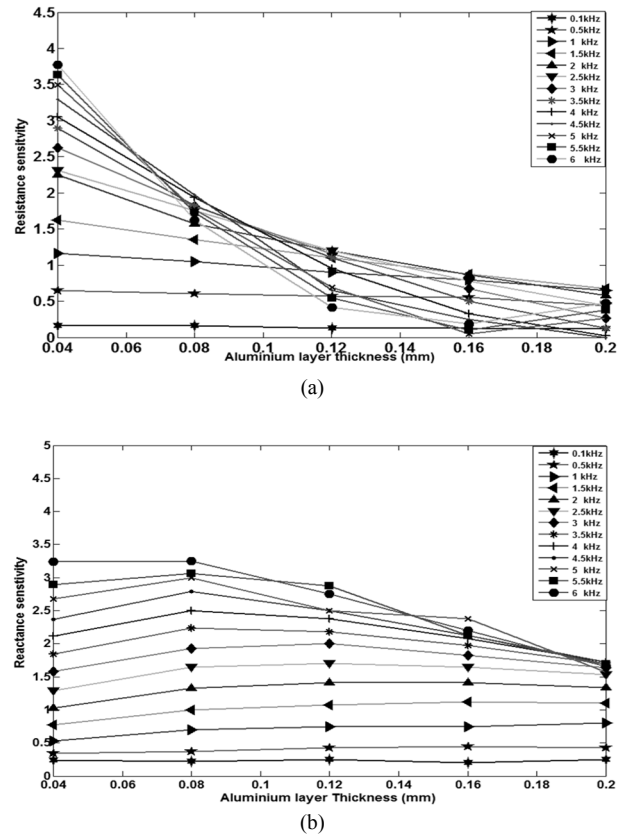

Fig. 3. Resistance and reactance sensitivities vs. Aluminium layer thickness
for different frequencies
(a) resistance sensitivity, (b) reactance sensitivity.

Let us taking the sensitivity threshold S_{th}=1, and consider only frequencies having sensitivity greater than S_{th}. It is well observed that the resistance has a poor sensitivity according to the selected sensitivity threshold, especially for Aluminum layer thicknesses greater than 0.16 mm (Fig.3.a). However, for frequencies greater than 2 kHz good reactance sensitivity is observed (Fig.3.b). Thereafter only the reactance is taken into account and that for frequencies greater than 2 kHz so $f_o>$ 2kHz. Now, let us consider the second criterion; looking for the best linear relationship between the normalized reactance

X_n and the Aluminum layer thickness and that for frequencies $f_o > 2$ kHz. Thus, let us approximate the curves shown in Fig. 2.b by a set of linear equations as:

$$\hat{X}_n = a.e + b \qquad (5)$$

$\hat{X}_n$ is a linear approximation of X_n. As a result, a set of equations similar to (5) are formulated and that for frequencies greater than 2 kHz. The coefficients a and b are given by using the beginning and ending points of curves as:

$$a = \frac{e_1 - e_2}{X_{n1} - X_{n2}} \qquad (6)$$

$$b = e_1 - aX_{n1} \qquad (7)$$

Where (e_1, X_{n1}) corresponds to the beginning point and (e_2, X_{n2}) corresponds to the ending point (Fig. 2.b). For example, for the frequency 6 kHz, (e_1, X_{n1}) equal to (0 mm, 1.3) and (e_2, X_{n2}) equal to (0.2 mm, 0.8). $e_1=0$ mm signify that the material is free from the Aluminium layer. Let us define the linearity indicator L_{ind} as follows:

$$L_{ind} = \frac{100}{m} \sum_{k=1}^{m} \left| \frac{X_n(k) - \hat{X}_n(k)}{X_n(k)} \right| \% \qquad (8)$$

In (8) m is the number of the computed points for each frequency i.e.m=6. For example the linearity indicator for 6 kHz is L_{ind}= 3%. In the fact L_{ind} corresponds to the error of the linear approximation given by equation (5). By the way, a best linear relationship corresponds to the minimum L_{ind} which is observed for 3 kHz (Fig. 4). Accordingly, the looking-for optimal working frequency is f_o =3 kHz that allow a good linear approximation with L_{ind} = 0.02%.
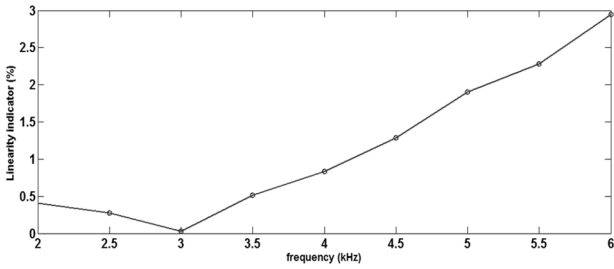

Fig. 4. Linearity indicator L_{ind} for f> 2 kHz

From the previous, the appropriate working frequency is 3 kHz, and so, its corresponding linear approximation will be integrated afterward in the Labview application of the experimental setup.

III. EXPERIMENTAL SETUP

The experimental setup is realized with three main components: the eddy current sensor, the RLC-meter and the laptop in which the Labview application is developed. These components are connected as shown in Fig. 5. Note that the working frequency is 3 kHz and its corresponding linear equation (5) is integrated in the Labview application (Fig.6).The Labview application is developed within two steps:

- Creation of a Labview RS232 driver for the RLC-meter instrument.
- Development of the Labview Block diagram and its corresponding front panel.
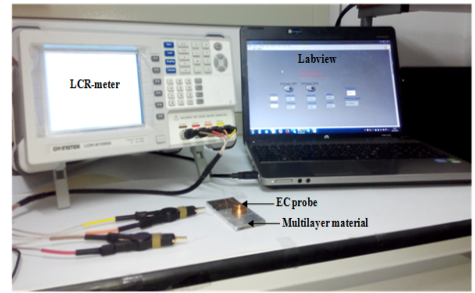

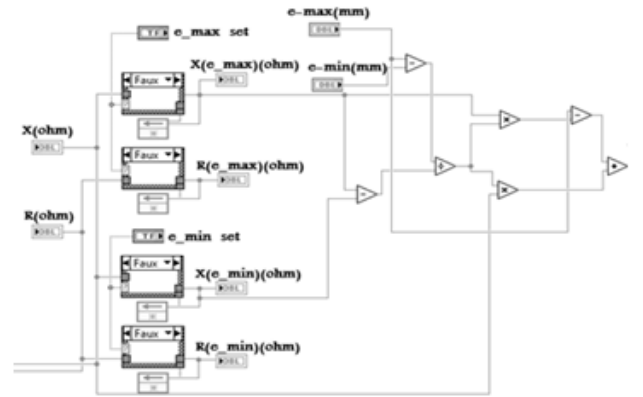Fig. 5. Aluminium layer thickness measurement in multilayer steel material, the experimental setup

Fig. 6. Labview block diagram of equation (5)

The measurement of the Aluminium layer thickness is carried out as follows; once the eddy current sensor placed above the multilayer material, both resistance and reactance are displayed in the Labview application front-panel (Fig. 7), as well as the Aluminium layer thickness.
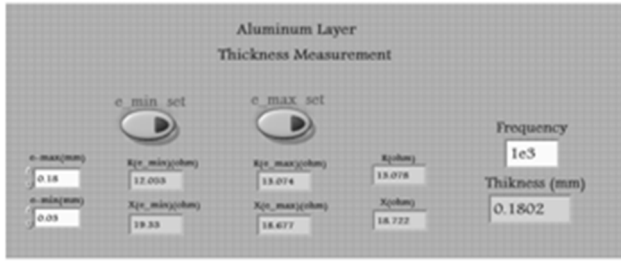
Fig. 7. Front-panel of the developed Labview application

IV. RESULTS

Some experimental samples of multilayer materials containing Aluminium layer with different thicknesses ranging from 0.03 mm to 0.18 mm are prepared. Table II and Fig. 8 give the exact known thicknesses and those measured by using the realized experimental setup.

TABLE II. Aluminium thickness measurement

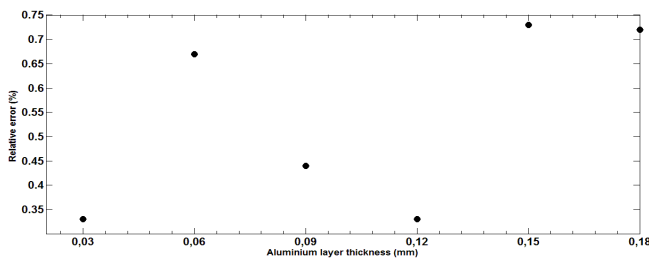| Exact thickness [mm]	Measured thickness [mm]	Relative error [%]	Average error [%]
0.03	0.0299	0.33	
0.06	0.0604	0.67	
0.09	0.0904	0.44	0.54
0.12	0.1204	0.33	
0.15	0.1511	0.73	
0.18	0.1813	0.72	

Fig. 8. Relative error of the measurement

These results confirm a good accuracy of the measurements carried out with the experimental setup; note that the maximum relative error doesn't exceed 1%.

V. CONCLUSION

In this paper, an eddy current sensor based system is realized for Aluminium layer thickness measurement in multilayer material. The relationship between the sensor reactance and the Aluminium layer thickness has been obtained by the electromagnetic analytical model of Dodd and Deeds, and followed by implemented in the developed Labview application. The optimal working frequency is selected according to the sensitivity and the relationship linearity of the sensor. Some experimental samples of multilayer material containing Aluminium layer with different thicknesses are prepared and measured. The measured thicknesses compared

to exact ones, show the good accuracy of the experimental setup where the maximum relative error doesn't exceed 1%.

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