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PAPERS

3D surface crack characterization by eddy current array image and a fast algorithm search

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Nowadays, 3D eddy current nondestructive characterization of crack and corrosion defects while using ECA remains an industrial challenge because the obtained image permits to determine only the 2D defect shape. Consequently, this article is devoted to determine directly the crack length and width by eddy current images through sensor array. Afterwards, we extract the maximal impedance amplitude to estimate the crack depth while using the deterministic algorithm that we have recently developed. In fact, the obtained results have demonstrated the effectiveness and the reliability of the proposed method.

K e y w o r d s: eddy current sensor, crack, characterization, 3D finite elements, simplified signal

1 Introduction

The fracture of a piece in a given structure can cause a succession of catastrophic events that will destroy other parts or equipment in good condition, in need of refurbishment and much longer costly downtime [1]. In less severe cases, these fractures can cause the retirement of machinery and systems stopping the production. In the industrial applications, several objectives are aimed by eddy current nondestructive testing (EC-NDT) [1, 2]. For example many companies such as Eddyfi, Olympus, Zetec and other societies uses eddy current array technology which offers major advantages over conventional eddy current inspection methods. Because each individual eddy current coil generates a unique electrical signal in relation to the structure below it, the coils can detect very small changes in material thickness, along with other parameters, and display these changes as a color-coded C-scan image. Imaging using eddy current array allows easy interpretation of the data generated from the probe coils. After it has been collected, the inspection data can be stored, transmitted, and analyzed. Color palettes play a very important role in the imaging of eddy current array data. However, the obtained image remains relatively a qualitative 2D description of the affected zones; because the defect depth is not known. In our case, the objective is to identify the crack length L_{d}, and width W_{d} from the 2D eddy current array image[3, 4]. Then, we use the sensor resistance Rmes as an input in an algorithm composed of 3D-FEM implemented in Comsol-Multiphysics and deterministic algorithm search to determine the defect depth D_{d}, [5]. Finally, the crack size and shape can be easily reconstructed.

2 Mathematical model

The adopted 3D electromagnetic model is given by, [6, 7]

$$\frac{1}{\mu}\big(\vec{\nabla}\times\vec{\nabla}\times\vec{A}\big)+\sigma\frac{\partial\vec{A}}{\partial t}=\vec{J}_{\mathrm{s}}, \tag{1}$$

where $\vec{A}$ is the magnetic vector potential, μ - is the magnetic permeability, and σ - is the electrical conductivity of the plate, $\vec{J}_{\mathrm{s}}$ is the coil current density, and t - is the time.

The sensor impedance variation is determined by calculating the magnetic energy stored throughout the study space and the Joule losses in the conductor for the part without fault (E_{s}) and with defect (E_{d}).

The sensor impedance is

$$\Delta Z=\Delta R+j\omega\Delta X,$$

where, ΔR and ΔX are, [9–11]

$$\begin{gathered}\Delta R=\frac{E_{\mathrm{J}}^{\mathrm{s}}-E_{\mathrm{J}}^{\mathrm{d}}}{I^2},\quad \Delta X=\frac{2\omega\big(E_{\mathrm{M}}^{\mathrm{s}}-E_{\mathrm{M}}^{\mathrm{d}}\big)}{I^2},\\ E_{\mathrm{J}}=\frac{1}{\sigma}\int_{\mathrm{con}}\vec{J}\cdot\vec{J}^{*}\mathrm{d}v,\quad E_{\mathrm{M}}=\frac{1}{2\mu}\int_{\mathrm{spc}}\vec{B}\cdot\vec{B}^{*}\mathrm{d}v,\end{gathered} \tag{2}$$

where $\vec{B}$ and $\vec{J}$ are respectively the magnetic induction vector and the current density vector, and I is the supply current.

3 Advantages of the multiplexed ECA

With a classic probe having only one element and more especially in the setting of the inspection of the plane

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Table 1. Physical and geometrical parameters of the studied device, [4]

Conductive Plate		Coil		Crack	
Length (L_p)	50 (mm)	Inner radius (R_i)	0.5 (mm)	Length (L_d)	20 (mm)
Width (W_p)	50 (mm)	Outer radius(R_o)	1.5 (mm)	Depth (D_d)	2 (mm)
Depth (D_d)	5 (mm)	High(h)	2 (mm)	Width (W_d)	3 (mm)
Conductivity (σ)	1.7×10 (S/m)	Number of turns (N)	200	Frequency	16 (kHz)
Permeability (μ_r)	1	Lift-off	0.5 (mm)		

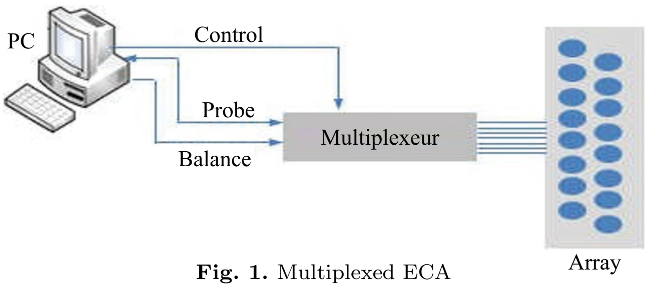

Fig. 1. Multiplexed ECA

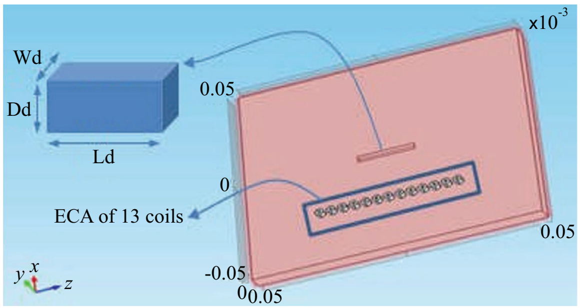

Fig. 2. Constitution of the studied device

surfaces, the mechanism of broadcast-receipt used most of the time necessarily entails the conception of pencil probe. To improve the resolution means to increase the length of inspection that can become relatively long typically. The use of ECA can palliate this problem. Indeed, a matrix of sensitive elements permits to do a multiple number of measures simultaneously, without movement of the probe. Such matrix permits to save as many displacements therefore, while replacing the mechanical sweep by an electronic one through the multiplexer [12], Fig. 1

On the other hand, the interest ECA is then to be able to do some measures successively with induced currents in several senses. It is then possible to combine the different measures, in order to succeed to more complete information permitting to detect the shortcomings regardless of their orientation in the plan of inspection.

4 Studied device description and results

The eddy current NDT system is composed of a plate presenting a parallelepiped crack an eddy current array composed of 13 coils as shown in Fig. 2.

The simulation of any electromagnetic system needs the knowledge of all physical and geometrical characteristics in different regions. The physical and geometrical parameters of the studied system are given on Tab. 1, [4].

5 Studied device description and results

After implementing the previous system under COMSOL-Multiphysics, we have determined the 2D and 3D cartographies of the sensor impedance variation [13,14], the resistance, reactance and the amplitude of the impedance variation as shown in Fig. 3 to Fig. 8.

From presented figures, one can deduce that the resistance variation cartography gives a very precise representation of the defect location, shape and size. Thus, the relative error is about 0.05 % for the defect length and about zero for defect width. However, the defect depth remains unknown and must be estimated because it represents the dangerousness of the detected crack. For this reason, the following sections will be reserved to the description of the inversion method allowing us to estimate the crack depth.

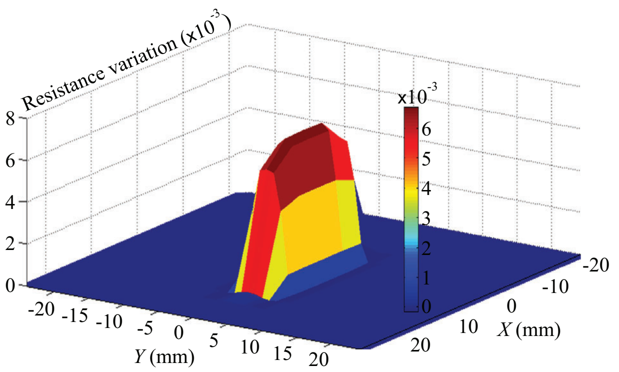

Fig. 3. Cartography of the resistance variation, 3D view

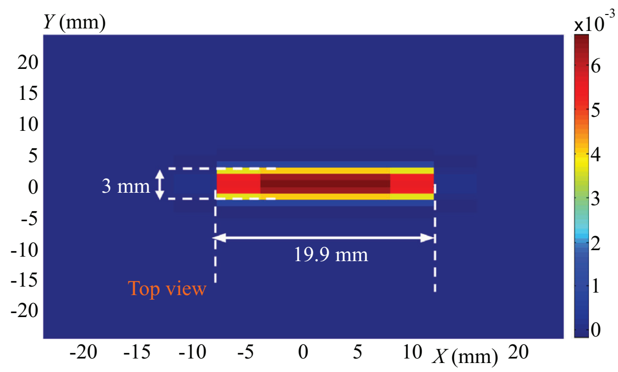

Fig. 4. Cartography of the resistance variation, Top view

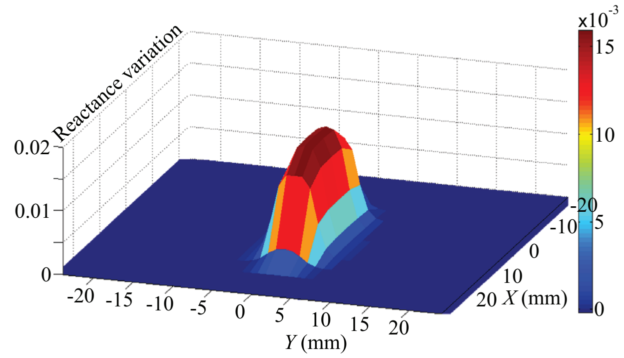

Fig. 5. Cartography of the reactance variation, 3D view

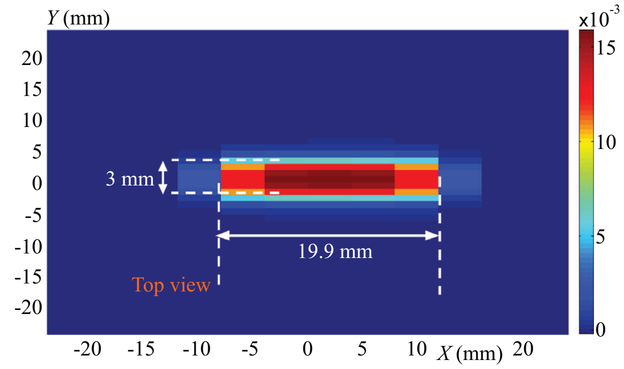

Fig. 6. Cartography of the reactance variation, Top view

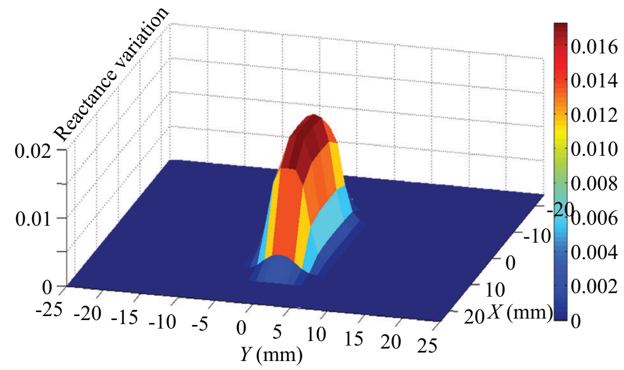

Fig. 7. Cartography of the amplitude variation, 3D view

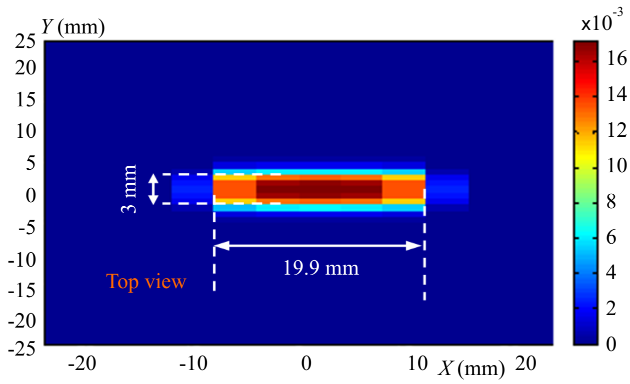

Fig. 8. Cartography of the amplitude variation,Top view

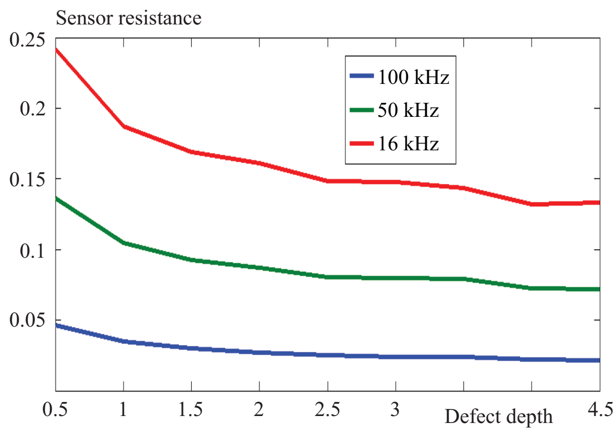

Fig. 9. Sensor resistance according to defect depth for $f = 16$ kHz, 50 kHz and 100 kHz

6 Development of the inverse method for crack depth measurement

After implementation the FEM on Matlab software, we have studied the effect of crack depth (D_{d}) on the sensor resistance. The yielded results are given in Fig. 9.

From these results, we remark clearly that the resistance R decreases with the increase of the crack depth D_{d}, [15]. Furthermore, greater variations are obtained for high frequencies because the defect is on the surface. Our objective in this section is not to make a deep analysis of these results because this problem is already treated in previous works. For this reason, the next section is devoted to exploit the developed forward model for resolving the inverse problem which consists in measuring defect depth D_{d}, [16]. The inverse method that we propose in this contribution is based on the association of the 3D forward FEM and an algorithm research [3]. The algorithm exploits the fact that the sensor resistance R according to crack depth D_{d} is a decreasing function. While knowing the physical and geometrical parameters of the studied system and the starting interval limits: $D_{\mathrm{d,min}}$ and $D_{\mathrm{d,max}}$, the forward model determines the sensor resistance R_{mes} corresponding to the intermediate crack depth

$$D_{\mathrm{d,int}} = \frac{D_{\mathrm{d,min}} + D_{\mathrm{d,max}}}{2}$$

If the calculated resistance R is lower than R_{mes}, the crack depth $D_{\mathrm{d,min}}$ is replaced by $D_{\mathrm{d,int}}$

This process is repeated until the difference $(|R - R_{\mathrm{mes}}| \le \epsilon)$, becomes lower than the tolerance ϵ. These process steps are summarized in Fig. 10.

This algorithm presents several advantages such as: the solution is guaranteed in advance if the sought value belongs to the starting interval. Certainly, in the industrial applications the experts know the starting interval of crack depth ($D_{\mathrm{d,min}}$ and $D_{\mathrm{d,max}}$).

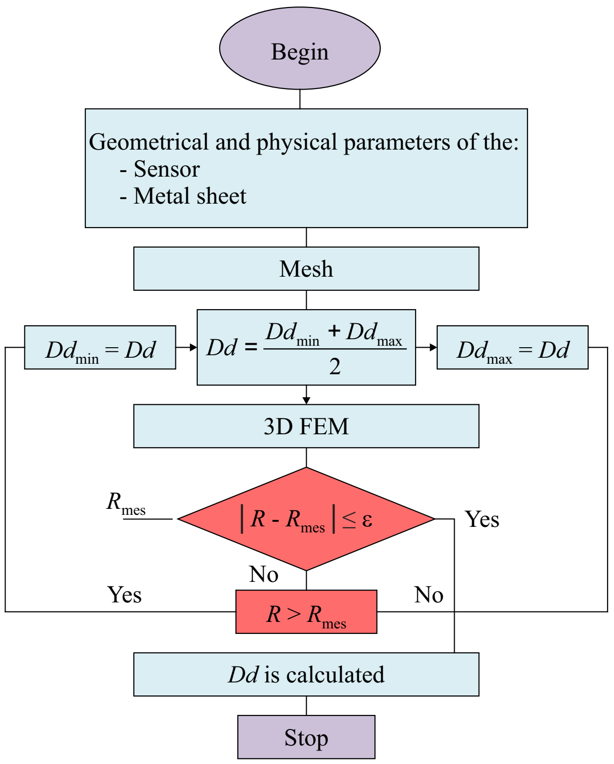

Fig. 10. Flowchart of deterministic algorithm search

We applied the developed inverse method to determine the crack depth of Aluminum plate. Hence, the evolution of the crack depth, for exciting field frequency of 150 kHz, according to iteration number is shown in Fig. 11, [8, 14].

The results obtained by the proposed method are very precise and close to the desired ones. They show the robustness of this method. In fact, 5 iterations are sufficient to determine the crack depth (3 mm). Also, we know that probabilistic methods such as genetic algorithm are very expensive in computation time because of the high number of objective function evaluations for each iteration. Alternatively, to achieve an acceptable accuracy, the population size must be increased what induce a significant computation time. As a result, the proposed method is more preferred; because it is faster and its performance does not change when the calculation is reset, which is not the case for the other stochastic methods [17, 18]. Therefore, the following figure summarizes the different steps for 3D crack reconstruction.

7 Conclusion

In this paper, after coupling Comsol-Multiphysics with Matlab software, we have exploited a graphical shape of the sensor signal obtained for a complete sweep along the defect axis. In fact, the precious remark consists in the possibility to deduce directly that the crack length L_{d} and width W_{d} from the 2D resistance variation cartography. After that, while knowing the L_{d}, W_{d} and R_{mes} we exploited the deterministic algorithm that we have recently developed to determine defect depth [8].

Accordingly, after implementing and running the inversion technique under Matlab environment, the simulation results calculate the crack depth D_{d}. Advantageously, the calculation results has demonstrated the rapidity and robustness of the proposed method while making a judicious configuration choice for initial parameters such as initial interval search ($D_{\mathrm{d\ min}}$ and $D_{\mathrm{d\ max}}$). In fact, while using this algorithm, few iterations are sufficient for real time reconstruction of 3D cracks. In future work, we intend to apply this procedure to characterize a defect with arbitrary shape such as nonuniform corrosion.

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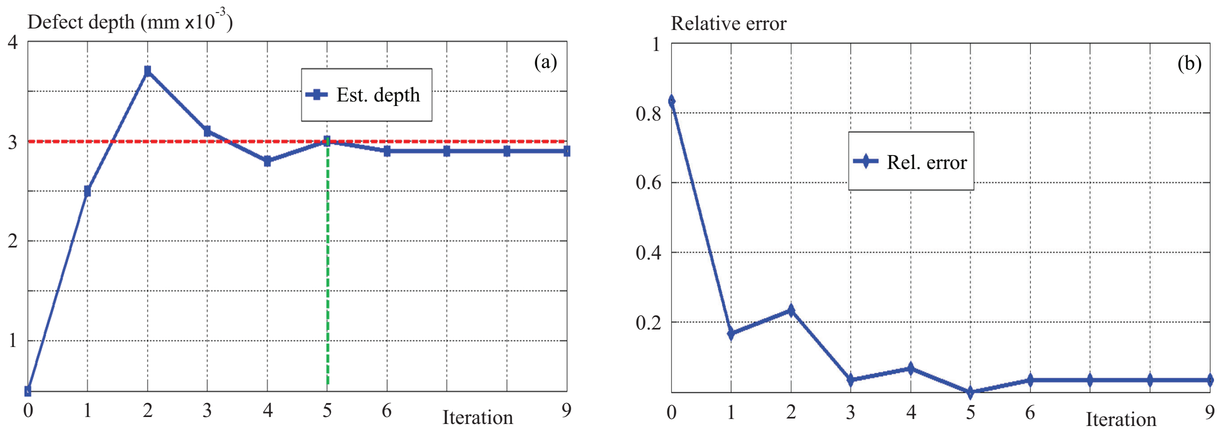

Fig. 11. Defect depth and relative error according to algorithm iteration

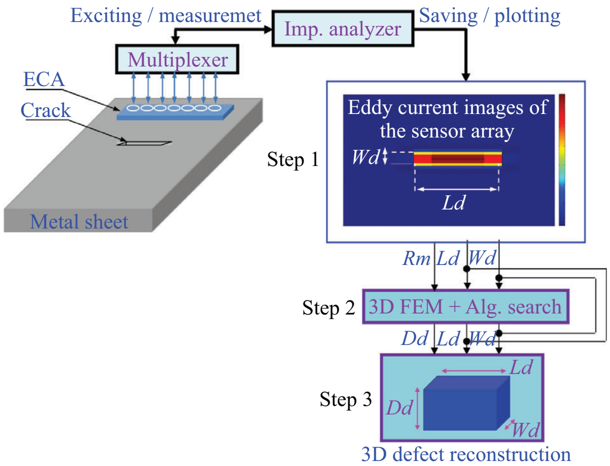

Fig. 12. Summarization of different steps for 3D crack reconstruction

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