Journal of Engineering and Technology for Industrial Applications

ISSN ONLINE: 2447-0228

ITEGAM-JETIA

Manaus, v.11 n.52, p. 87-91. March / April, 2025.

DOI: https://doi.org/10.5935/jetia.v11i52.1538

RESEARCH ARTICLEOPEN ACCESS

QUANTITATIVE ANALYSIS OF SUBSURACE STRUCTURE CRACKING USING PULSED EDDY CURRENT NONDESTRUCTIVE TESTING

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ARTICLE INFO

Article History
Received: January 07, 2025
Revised: February 20, 2025
Accepted: March 15, 2025
Published: March 31, 2025

Keywords:
Pulsed eddy current,
Metallic materials,
Nondestructive testing,
Finite element method,

ABSTRACT

This paper presents a three-dimensional finite element method for the nondestructive evaluation of forward problems utilizing the pulsed eddy current technique. The method visualizes and maps the distribution of responses resulting from the interaction between eddy currents and defects, facilitating defect characterization. The study elaborates on the defect characterization process using the pulsed eddy current technique, which encompasses both numerical and experimental analyses. Initially, the variation in pulse width of the pulsed eddy current technique is discussed, along with its effectiveness. Subsequently, the investigation into the application of pulsed eddy current testing for defects is conducted through the mapping of magnetic field distributions, implemented via time-stepping three-dimensional finite element modelling, with features extracted from the mapping for the purpose of defect characterization.

I. INTRODUCTION

Nondestructive testing (NDT) refers to a comprehensive array of inspection techniques and methodologies designed to assess and monitor the condition of materials, components, or equipment without altering their inherent properties or performance. This practice is vital for ensuring the maintenance and reliability of components, thus preventing accidents, loss of life, and both economic and environmental repercussions. However, there is a pressing need for technological research and development (TR&D) to cultivate scientific knowledge in this domain, especially in light of the growing prevalence of products utilizing new materials and advanced manufacturing technologies that impose stringent safety requirements [1]. The detection of micro defects, both on the surface and beneath it, using NDT methods like Eddy Currents (EC) poses considerable challenges [2]. The key difficulties include firstly the minimum detectable defect size is often insufficient due to noise from probe vibrations (lift-off) that can mask the defect signal; secondly the complexity of generating tailored EC patterns in the materials under inspection; and finally that the intricate design of probes, which frequently consist of numerous assembled elements within a single configuration. The main goal for this paper, is to develop applied research, innovation, numerical simulation, and knowledge generation for creating customized Non-Destructive Testing (NDT) systems using pulsed eddy currents (PEC) [3]. A secondary goal focused on technological innovation to design and experimentally validate custom eddy current systems for three demanding engineering applications: inspecting micro defects in plane structures, and evaluating brazed joints in the automotive sector. This involved starting with the scientific principles of NDT using EC, analyzing and characterizing materials, designing and simulating puled eddy current probes, and testing prototypes in real industrial settings. At the same time, some of them pose scientific challenges that require new procedural knowledge and deeper research, as they involve concepts, theoretical foundations, materials, manufacturing processes, and geometries that have not been systematically studied in NDT before.

II. PRACTICAL USE O EDDY CURRENTS IN FLAW DETECTION

The main object of search when inspecting parts in operation is a fatigue crack, as a rule, coming to the surface. The geometric parameters of the crack are characterized by: length L is the maximum longitudinal size of the defect visible on the test surface, width B is the transverse dimension of the defect at its exit to the surface, depth H is the size of the defect towards the inside of the test surface. Since defects are often of a complex shape, there are maximum, minimum, average, and total values of these parameters. For subsurface defects, an important parameter is not only geometrically (e.g. diameter), but also distance from the surface – Z – depth [4].

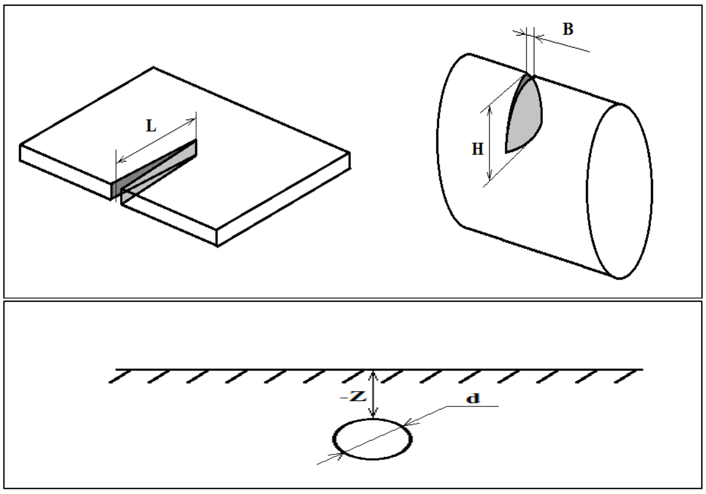

Figure 1: Geometric dimensions of defects.
Source: Authors, (2025).

With:
L – length; B is the width of the opening; H – depth; -Z – depth of occurrence; d – diameter

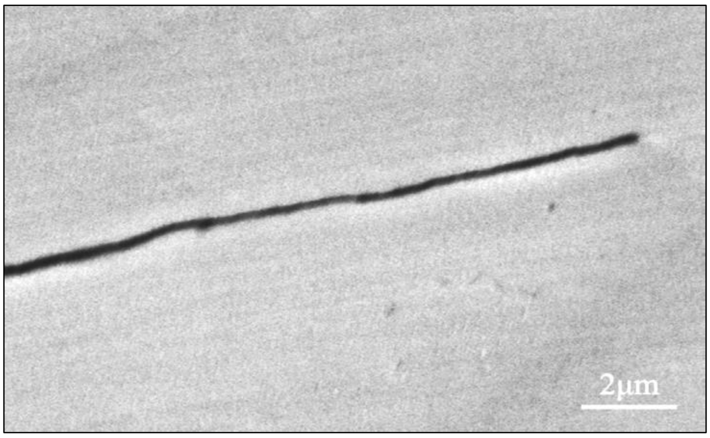

Figure 2: Transgranular stress corrosion cracking.
Source: Authors, (2025).

When conducting eddy current flaw detection, in order to select the optimal testing parameters, it is important to distinguish the direction of defect development. From this point of view, a distinction is made between longitudinal or transverse (relative to the longitudinal axis of the tested object or the direction of scanning with an eddy current transducer) cracks. With the help of feed-through transducers, it is possible to control the geometric dimensions and electromagnetic or related structural parameters (hardness, mechanical stresses, degree of fatigue damage, etc.) of rods, including those made of ferromagnetic materials [5]. At the same time, the frequency of the excitation current is an important parameter, the choice of which is determined by the required depth of penetration of eddy currents (depending on the task to be solved in the process of monitoring) [6]. On the one hand, the depth of penetration of eddy currents in a cylindrical object is somewhat greater than in a half-space with a flat surface, on the other hand, the density of eddy currents on the axis of the cylinder is equal to zero, regardless of the value of the generalized eddy current control parameter. To analyse the test results, as a rule, hodographs of the relative voltage of the measuringwinding are used by changes in amplitude, phase, and in some cases higher harmonics of which the degree of influence of the monitored or interfering parameters is judged.

In the practice of pulsed eddy current non-destructive testing, such informative features of signals are most often used, such as the displacement of the moment of crossing by a signal of a certain level, the time interval between certain nodal points or the peak values of the amplitude and the exceeding of the amplitude of certain threshold values and the moments of these crossings [7]. Currently, the disadvantage of this method is the use of individual characteristic points of the eddy current converter signal, that is, incomplete use of the information capabilities of the eddy current converter signal and the lack of protection of the above-mentioned point characteristics from the influence of interference. In addition, from the analysis of literary sources, it can be seen that the pulse excitation mode (PEM) of the eddy current allows to complement the traditional eddy current nondestructive control with harmonic excitation, however, today, in the conditions of rapid development of methods and means of signal analysis, the pulse excitation mode is insufficiently researched.

III. NUMERICAL MODELING AND RESULTS

In the field of ECNDT, numerical modeling has emerged as a crucial tool in the design of probes and the analysis of detection performance, largely due to advancements in computing power. Generally, the modeling of ECNDT relies on the resolution of Maxwell's equations [8]. Depending on the complexity of the configuration being simulated, the resolution may be either analytical or numerical. The analytical solution of Maxwell's equations is advantageous due to its speed and the high precision of results it yields. However, the intricate nature of eddy current configurations often renders an analytical solution unattainable. Consequently, an alternative approach involves the application of numerical methods, which facilitate the examination of a wider range of probeworkpiece configurations, including various geometries of components, defects, and sensors [9].

In scenarios where it is essential to differentiate multiple parameters, the Pulsed Eddy Current Control Method serves as a viable alternative to multi-frequency excitation. The latter often encounters limitations due to the complexity of the apparatus and the challenges associated with practical implementation, which restrict the number of usable frequencies. In pulsed eddy current control, excitation currents in the form of rectangular, trapezoidal, or half-sinusoidal pulses are introduced into the sensor.

This study also incorporates a wave derived from a capacitive discharge [10]. The Fourier series decomposition of this wave produces signals across various frequencies. Instead of utilizing the normalized impedance plane for signal analysis, a time or frequency-based approach is adopted. The characterization of the target quantity is achieved by examining the behaviour of specific points within the signal, including zero crossings, extrema, and the fixed point (crossing-point), which remains unaffected by variations in the sensor-load air gap [11].

The evolution of these points facilitates diagnostic assessments. Spectral analysis has demonstrated that the fixed point phenomenon is relevant to transient signals and their harmonics, with the variations in the coordinates of this point being predictable based on conductivity and thickness. Further investigation into the origins of this phenomenon and its potential applications is warranted. The transient magnetic field is expressed in terms of magnetic vector potential, and source current density (SCD)

$$-\nabla \cdot 1/\mu \ \nabla A + \sigma \frac{\partial A}{\partial t} = J \quad (1)$$

Consider the problem JSAEM#6 illustrated by figure 3. The finite element mesh contains 79162 nodes and 1021837tetrahedral elements. A preconditioning technique, called the symmetric successive over-relaxation (SSOR) method is employed to minimize computation time and memory [12]. The summary of the geometric and physical quantities is shown in table 1.

Table 1: Geometric and physical parameters of the JSAEM#6 Benchmark

Parameter	Value [mm]
Plate thickness	1.25
Plate length	140
Plate width	140
Conductivity [MS/m]	1.00
Crack width	0.20
Crack length	10.0
Crack depth	0.75
Frequency[kHz]	150 & 300
Coil inner radius	0.60
Coil outer radius	1.60
Coil height	0.80
Lift-off	0.22

Source: Authors, (2025).

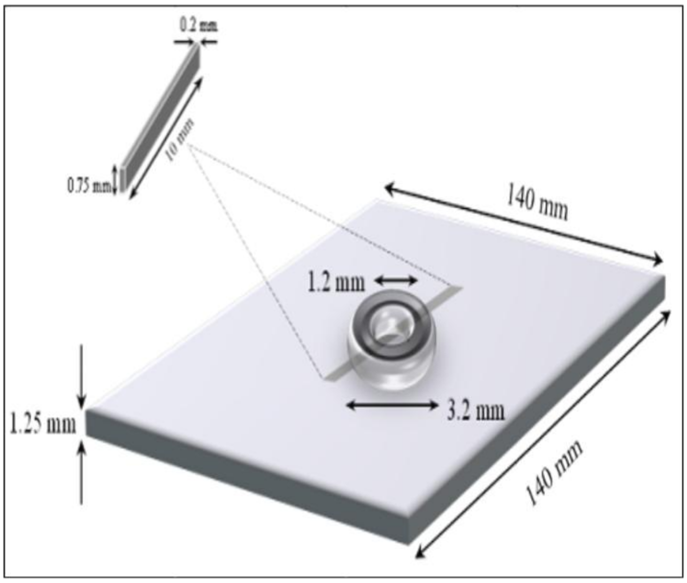

Figure 3: Geometrical Model with Crack.
Source: Authors, (2025).

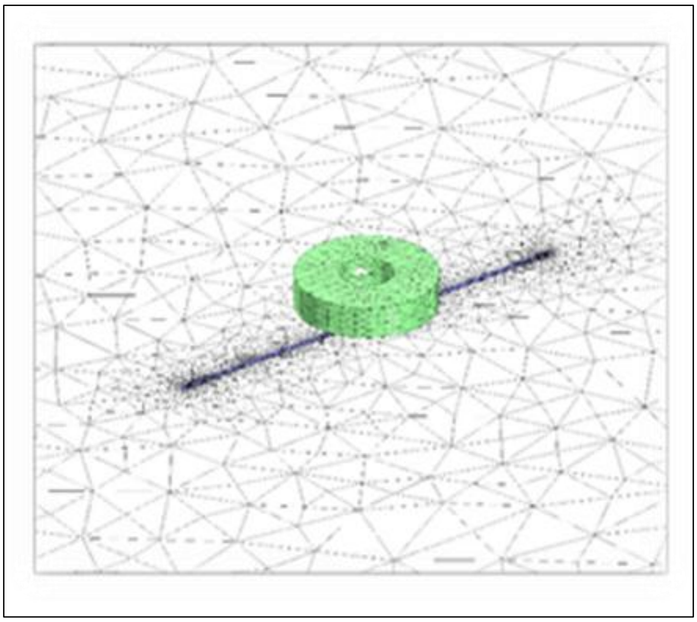

Figure 4: Tetraedral meshing model.
Source: Authors, (2025).

Under the given frequency and coil lift-off, the impedance is calculated as function of coil position [13]. The impedance change represented respectively by the resistance and reactance components in figure 5, is evaluated by subtracting the values obtained for the plate without crack from the values obtained for the plate with crack. We remark a good agreement between experimental and calculated results.

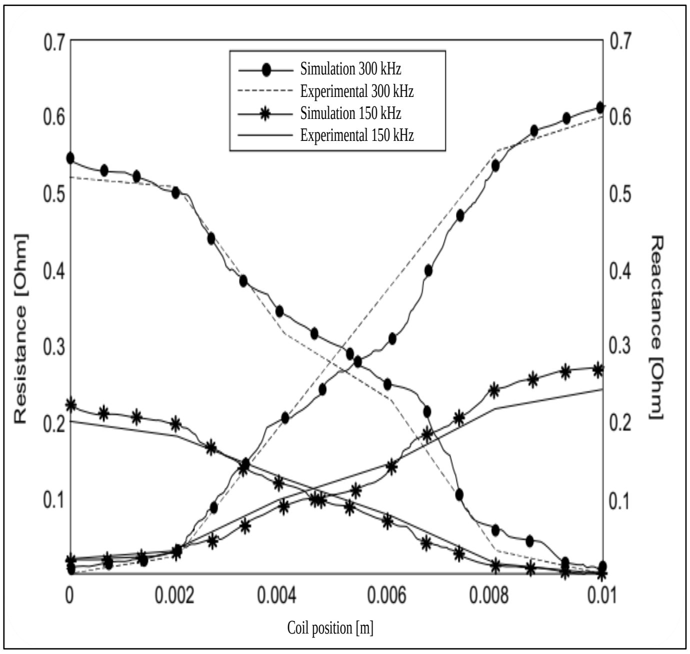

Figure 5. Experimental and numerical evolution of impedance components vs displacement coil.
Source: Authors, (2025).

Consider the model of figure 6 with three notches on the surface of the Bench-mark along its width, each opening equal to 2 mm [14]. The depth of these cuts varies between three different values: 80%, 55% and finally 25% of the benchmark height structure equal to 1.25 mm [15]. The excitation current is in the form of a quasi-square wave as shown in Figure 6.

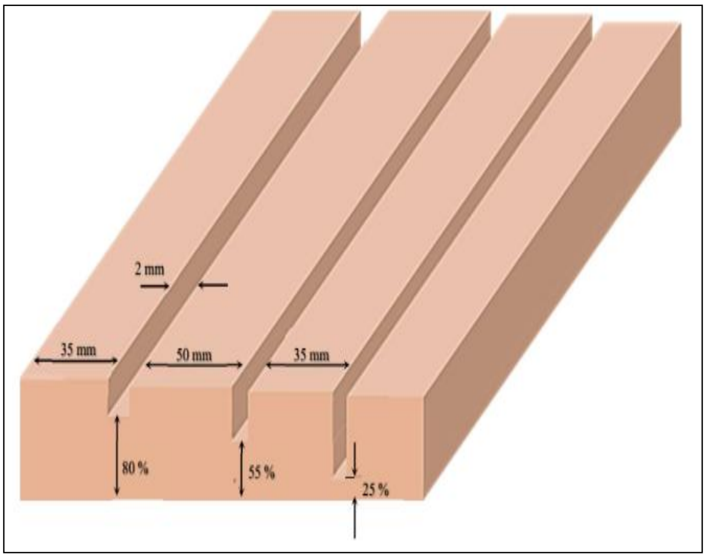

Figure 6: JSAEM# 6 configuration with notches.
Source: Authors, (2025).

The excitation current has the shape of a quasi-square wave as shown in figure 7. The expression of the current introduced is given by the following equation:

$$I(t) = I_0 \left\{ \begin{matrix} \left[\lambda + \frac{1}{T}\tau e^{-\frac{\lambda T}{\tau}}\left(1 - e^{\frac{T}{\tau}(2\lambda-1)}\right)\right] + \\ \frac{1}{\pi}\sum_{l=1}^{\infty}\left[a_l \cos\left(\frac{2l\pi t}{T}\right) + b_l \sin\left(\frac{2l\pi t}{T}\right)\right] \end{matrix} \right\} \quad (2)$$

with:

$$I_0 = 0.5\,A,$$
$$\lambda = 50\%\,,$$
$$\tau = 50\ \mu s,$$
$$\frac{1}{T} = 100\ Hz$$

The constants a_1 and b_1 are given by the following expressions:

$$a_l = \frac{\sin(2l\lambda\pi)}{l} - \frac{2\pi}{T}\left[\frac{1}{\tau^2} + \left(\frac{2l\pi}{T}\right)^2\right]^{-1} \left\{ \begin{matrix} \frac{1}{\tau}\left[1 + e^{\frac{T(\lambda-1)}{\tau}}\right] + \\ \left[\frac{2l\pi\sin(2l\lambda\pi)}{T} - \frac{\cos(2l\lambda\pi)}{\tau}\right]\left(1 + e^{-\frac{\lambda T}{\tau}}\right) \end{matrix} \right\} \quad (3)$$

$$b_l = \frac{1-\cos(2l\lambda\pi)}{l} - \frac{2\pi}{T}\left[\frac{1}{\tau^2} + \left(\frac{2l\pi}{T}\right)^2\right]^{-1} \left\{ \begin{matrix} \frac{2l\pi}{T}\left[1 + e^{\frac{T(\lambda-1)}{\tau}}\right] \\ \left[\frac{2l\pi\cos(2l\lambda\pi)}{T} + \frac{\sin(2l\lambda\pi)}{\tau}\right] \\ \left(1 + e^{-\frac{\lambda T}{\tau}}\right) \end{matrix} \right\} \quad (4)$$

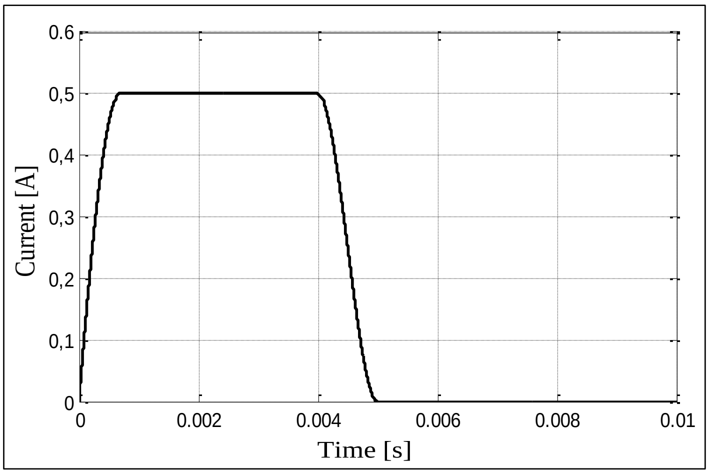

Figure 7: Excitations current shape.
Source: Authors, (2025).

Indeed, increasing the size of the crack defect increases the signal of the induced current issued by the eddy current sensor.

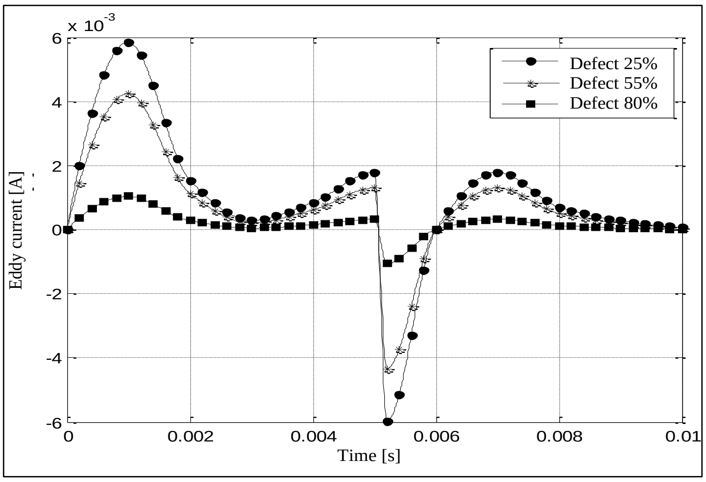

Figure 8: Effect of defect depth.
Source: Authors, (2025).

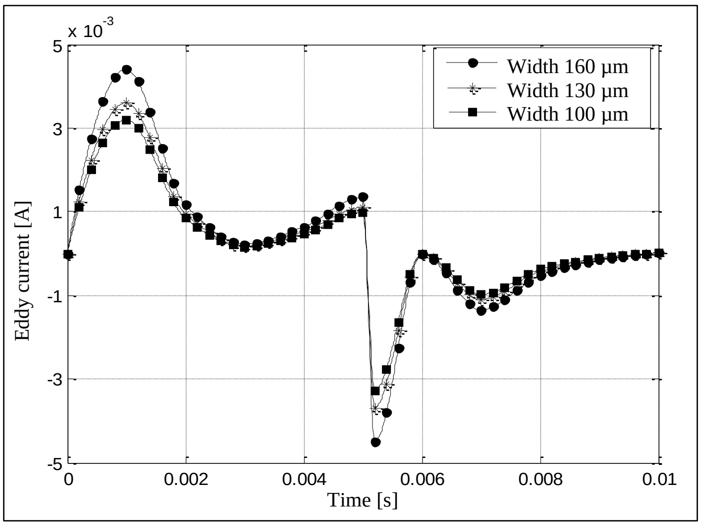

Figure 9: Defect width effect on induced current.
Source: Authors, (2025).

We note from these two figures 8 and 9 that the influence of the depth of the defect is much more visible and more important than the effect of the width which reinforces the concept of using the pulsed eddy currents for the measurement of the sheet thickness of flat or other structures [16]. Here, the width of the defect is maintained equal to 2 mm in the case of the two figures.

VI. CONCLUSION

The development of an eddy current control device, in sinusoidal or pulsed mode, requires the optimization of a certain number of parameters. This optimization is generally long and difficult to execute in practice since it results from several compromises. Several parameters can influence the response of a sensor including the sensor-target distance, the geometric parameters of the defect, and finally the electrical properties of the conductive part in this case the variation of the electrical conductivity. We can see that the maximum amplitude of the signal and the time necessary to have it are the main parameters necessary to identify defects. Applications using a Benchmark whose experimental results are available to validate our simulation results.

Numerical simulations are executed in advance of experiments that utilize the PEC technique to estimate the expected responses from defects. These simulations play a crucial role in shaping experimental designs, improving the understanding of the physics that govern specific defects, and enabling the extraction of features from the responses collected. Experimental investigations are subsequently conducted to validate the results of the simulations and to illustrate the practicality of the techniques used to gather information on particular defects.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Hakim Azizi, Mohammed chebout, Daoud Sekki, Mohammed Charif Kihal and Marouane Kihal
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Investigation: Hakim Azizi, Mohammed chebout, Daoud Sekki and Mohammed Charif Kihal
Discussion of results: Hakim Azizi, Mohammed chebout and Daoud Sekki
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Writing – Review and Editing: Hakim Azizi, Mohammed Charif Kihal and Marouane Kihal
Resources: Hakim Azizi, Mohammed Charif Kihal and Marouane Kihal
Supervision: Hakim Azizi, Mohammed chebout and Daoud Sekki
Approval of the final text: Hakim Azizi, Mohammed Charif Kihal and Marouane Kihal

VII. ACKNOWLEDGMENTS

The authors of this article would like to thank the General Directorate of Scientific Research and Technological Development (DGRSDT) in Algeria for their technical support and the specific research budget allocated to this program.

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