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Original scientific paper

A COMPARATIVE STUDY OF OPTIMIZATION METHODS FOR EDDY-CURRENT CHARACTERIZATION OF AERONAUTICAL METAL SHEETS

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Abstract. *This paper presents eddy current non-destructive characterization of three aeronautical metal sheets by deterministic and stochastic inversion methods. This procedure consists of associating the finite element method with three optimization algorithms (Simplex method and genetic and particle swarm algorithms) simultaneously determine electric conductivity, magnetic permeability and thickness of Al, Ti and 304L stainless steel metal sheets largely used in aeronautical industry. Indeed, the application of these methods has shown the performance of each inversion algorithms. As a result, while doing a qualitative and quantitative comparison, it was found that the Simplex method is more advantageous in comparison with genetic and particle swarm algorithms, since it is faster and more stable.*

Key words: *Eddy Current Sensor, Inverse Problem, Genetic Algorithm, Simplex Method, Particle Swarm Optimization.*

1. INTRODUCTION

Eddy current non destructive testing is a well-known method for material characterization, which is sensitive to conductive materials properties, such as electrical conductivity and magnetic permeability [1].

In aeronautic domain, planes are periodically subjected to inspection and maintenance operations as is the case of Algerian airline maintenance society. In the non-destructive testing (NDT) division, the eddy current technique is often used for inspecting and evaluating plane sensitive parts. Among these applications, we perform measurement of thickness and electric conductivity of metal sheets [2-3].

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In industrial automatic application, several iterative inversion methods are used to accomplish this objective. In general, the flowchart constitutes an iteration buckle containing the forward model associated to an inversion algorithm. Consequently, we recall that the analytical forward method of Dodd and Deeds gives an exact solution but the skin and the proximity effects in the exciting coil turns are neglected [4-5].

The aim of this paper is to associate the finite element method (FEM) with the optimization ones to estimate thickness, electric conductivity and magnetic permeability of Al, Ti and stainless steel 304L metal sheets largely used in aeronautic construction. From this association there results a comparative study of starting search interval, global searching time and the relative error for both optimization methods in order to determine the more advantageous one in terms of reliability and rapidity.

2. AERONAUTIC CONSTRUCTION MATERIALS

An airplane cockle is made, in the majority of cases, of aluminum, because its volume density is very low and that presents an advantage in aeronautics. Additionally, this material is also much appreciated since it has a good resistance to corrosion and is easily malleable which makes construction of different parts easier [3].

On the other hand, stainless steel 304L is less sensitive to corrosion effect and ideal for piece machining and welding in aeronautics applications. Nowadays, Titanium is a key element of aeronautic and spatial construction since its use is justified by its attractive characteristics: incomparable holding to corrosion and oxidization, nonmagnetic, good thermal and mechanical resistance. In fact, with such properties, titanium alloy constitutes an element of major quality for planes conception**,** Fig. 1.

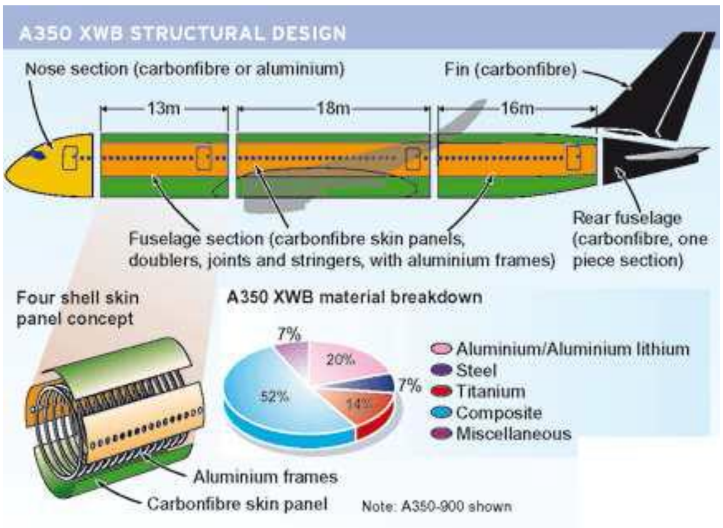

Fig. 1 Aeronautic construction materials [3].

3. Description of the Forward Model

The geometry of the considered problem is illustrated schematically in Fig.2. In this study, the metal sheet presents a flat surface with a thin nonconductive coating. In actual situation, when using an eddy current to measure thickness and electric conductivity, it is important to ensure that the other factors (geometry, the specimen temperature and lift-off) are kept under control [5,9]. A pancake-type, probe formed of coil is perpendicular to the tested metal sheet surface.

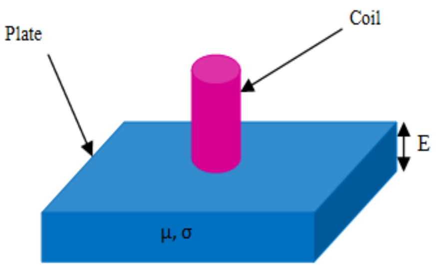

Fig. 2 Studied device configuration

The geometrical and physical characteristics are given in Table 1.

Table 1 Characteristics of the Modeled System

Coil	Values
Current intensity	0.04 [A]
Frequency	10 [kHz]
Inner radius	5.35 [mm].
Length	2.35 [mm].
High	2.3 [mm].
	Metal Sheet
Thickness	2 [mm].
Electric conductivity	That of Al, Inox 304L, Ti
Magnetic permeability	That of Al, Inox 304L, Ti

4. Mathematical Formulation of the Electromagnetic Forward Model

The Maxwell's equations, describing physical phenomena of Eddy current sensing [6-11] are defined as follows

$$\nabla \times \mathbf{H} = \mathbf{J}_s + \mathbf{J}\,, \tag{1}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}\,, \tag{2}$$

$$\nabla \cdot \mathbf{B} = 0\,, \tag{3}$$

where **H** is the magnetic field, **J** is the induced Eddy-current, $\mathbf{J_s}$ is the current density injected in the coils, **E** is the electric field, **B** is the magnetic flux density, and *t* denotes the time [7-12]. By considering constitutional relations linking the electromagnetic field to the properties of the material:

$$\mathbf{B} = \mu \mathbf{H}\,, \tag{4}$$

$$\mathbf{J} = \sigma \mathbf{E}\,, \tag{5}$$

where μ is the magnetic permeability, and σ is the electrical conductivity of the materials [13].Magnetic vector potential **A** is being defined as:

$$\mathbf{B} = \nabla \times \mathbf{A}. \tag{6}$$

Differential equation describing the Eddy current testing phenomena is then expressed by:

$$\frac{1}{\mu}(\nabla \times \nabla \times \mathbf{A}) = \mathbf{J}_s - \sigma \frac{\partial \mathbf{A}}{\partial t} \tag{7}$$

By considering the angular frequency ω and according to the condition of Coulomb-Gauge $\nabla \cdot \mathbf{A} = 0$, the electromagnetic equation in time-harmonic regime, using complex amplitudes [8] is expressed by:

$$\mathrm{rot}\left(\frac{1}{\mu}\mathrm{rot}(\mathbf{A})\right) = -\,\mathrm{j}\sigma\omega\mathbf{A} + \mathbf{J}_s \tag{8}$$

Where **A** represents the magnetic vector potential, j is the imaginary unit, ω is the angular frequency of the excitation current (rad/s), μ is the magnetic permeability of the media involved (H/m), σ is the electrical conductivity (S/m), and **J** is the current density (A/m^2) [10].

Finite element formulation for the 2D axisymmetric Eddy current phenomena was developed in many works. For axisymmetric geometries, Eq. (8) reduces to the 2D form [2,4].

$$\frac{1}{\mu}\left(\frac{\partial^2 A}{\partial r^2} + \frac{1}{r}\frac{\partial^2 A}{\partial r} + \frac{\partial^2 A}{\partial z} - \frac{A}{r^2}\right) = \mathrm{j}\sigma\omega A - J_S. \tag{9}$$

This equation describes the problem shown in Figure 3.

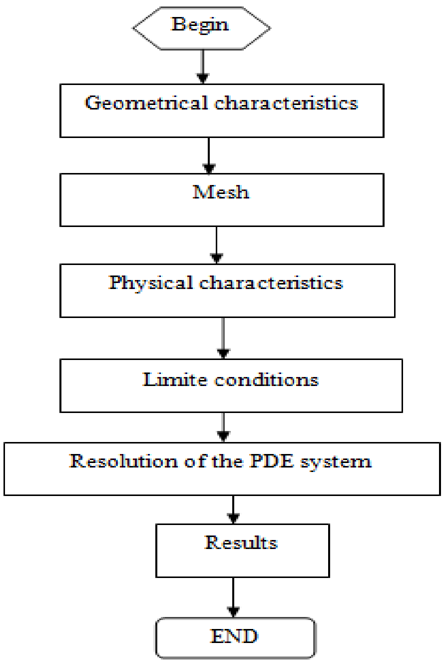

Fig. 3 Finite element modeling procedure

5. INVERSION STEPS

For the iterative inversion, the process is constituted of an iteration buckle containing the forward model that calculates the sensor impedance (*Zc*). The output (*Zc*) is compared to the measured value (*Zm*), than the obtained error is used by the optimization algorithm (genetic and particle swarm optimization algorithms) as an input in order to enhance the estimated parameters.

For each iteration, this strategy minimizes the obtained error (fitness function). Hence, the inversion process is accepted and stopped when the error is smaller than the tolerance [14,15]. We recall that in genetic algorithm (GA), firstly the population individuals are created according to a random process. Each individual takes a set of the evaluation parameters. Then, the fitness function is iteratively computed for all individuals. Following that, the couples are mixed, and during the mutation step this method through which populations' genetic variety is maintained from one generation to the next. In order to generate a superior population, the genetic operators were used in a way that was inspired by natural evolution [16].

On the other hand, the Simplex method is a very powerful local descent direct search method for minimizing a real-valued function. In each iteration, it begins with a simplex specified by n+1verticesand the associated function values. One or more test points are computed, along with their function values. At the end of each iteration, a new simplex is obtained, so as to satisfy some descent conditions regarding the values of the fitness function [17,18].

The inverse problem principle is based on the following steps:

Finding parameters of (E,σ,μ), and

Deducing values of *Z*c(E,σ,μ)=Zm.

With *Z*c is the impedance of the sensor and *Z*m is the measured impedance.

We have taken values from known properties **(**thickness, conductivity and magnetic permeability), and the measured values are replaced by those obtained by solving the direct problem by the finite element method.

Eq. (10) can be changed by minimizing the following fitness function:

$$S = \frac{1}{2}\sum_{i=1}^{n}\frac{[Z_i^m - Z_i^c(E,\sigma,\mu)]^2}{Z_i^m}, \tag{10}$$

where *n* is the length of the measurement array.

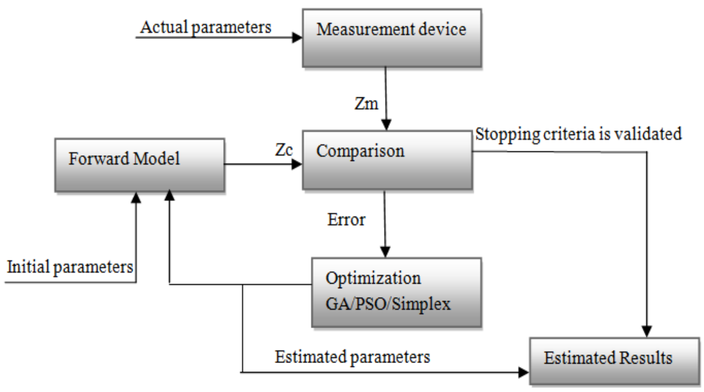

Fig. 4 Iterative inversion procedure

6. RESULTS AND DISCUSSION

An iterative inversion algorithm is elaborated in order to evaluate physical and geometrical properties of metal sheets (i.e. electric conductivity σ, magnetic permeability μ and thickness E). The inversion is achieved by stochastic methods, such as genetic and particle swarm algorithms combined with a deterministic one based on the Nelder-Mead algorithm associated to the finite element method (FEM) [9]. It uses selected evaluation parameters and gives the evaluated properties, Fig. 4.

Previous parameters and the fitness function according to iteration number are given in the following figures (Figs. 5-7). We recall that these results are obtained for Al, Ti and 304L stainless steel metal sheets for which the characteristics are reported on Table 2.

Table 2 Metal sheets characteristics

	Electric conductivity [MS/m]	Magnetic Permeability	Thickness [mm]
Al	37.7	1	2
Ti	2.52	25	2
Stainless steel 304L	1.36	160	2

6.1. Obtained results

To show the precision and the speed of the used inversion techniques, we have implemented them in Matlab environment. The obtained results are shown in the following figures:

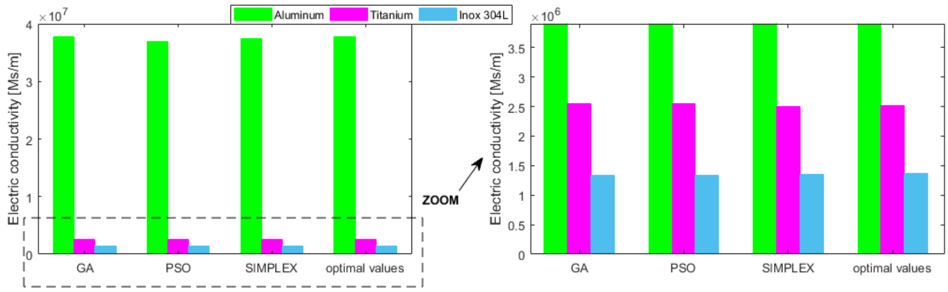

Fig. 5 Electric conductivity obtained for stainless steel, Aluminum and Titanium

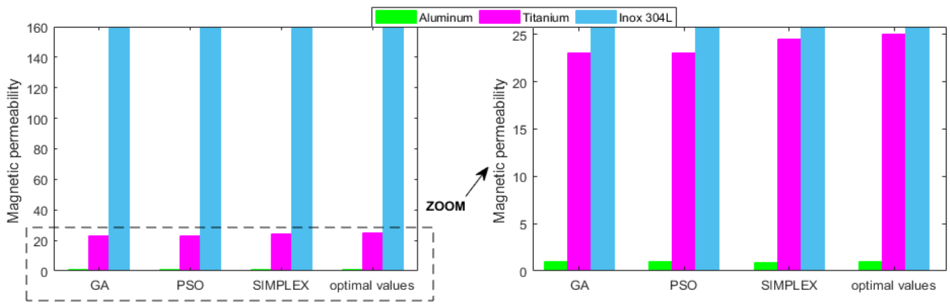

Fig. 6 Magnetic permeability obtained for stainless steel, Aluminum and Titanium

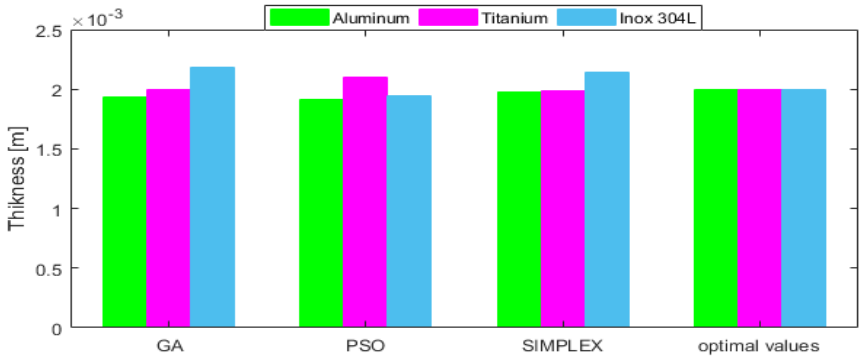

Fig. 7 Thickness obtained for stainless steel, Aluminum and Titanium

The computing time and the error rate between the real and estimated values of three optimization algorithms are summarized on Table 3.

Table 3 The results comparison of three optimization algorithms

		GA	PSO	SIM
Real Values		Estimated values	Estimated values	Estimated Values
Stainless steel 304L				
σ(MS/m)	1.36	1.34	1.34	1.35
μ	160	158	158	159
E(mm)	2	1.8	1.8	2
Al				
σ(MS/m)	37.7	37.5	37.6	37.6
μ	1	1.2	0.99	1
E(mm)	2	1.9	2	2
Ti				
σ(MS/m)	2.52	2.54	2.51	2.53
μ	25	23	24	25
E(mm)	2	2	2.3	2
Computing time (s)		1750	1420	224
Error (%)		1.08	1.02	0.35

6.2. Discussion

Through this application, we have noticed that the obtained results by using Simplex, genetic and particle swarm algorithms are very accurate and relate to the actual ones. Indeed, these results confirm the reliability and the robustness of the inversion procedure. Besides, we have deduced that GA and PSO are very slow in comparison to the SIM because of the height number of fitness function to be calculated for each iteration.

On the other hand, to reach a satisfactory precision, the population size has to be increased to a certain level since it increases calculation time. In fact, the SIM method is more privileged because it is faster and its algorithm performance does not change while restarting calculation. Nevertheless, the Simplex method introduces some issues like regulating parameters choice (reflection, expansion, contraction) and those of the starting step.

7. CONCLUSION

Periodically, aircrafts are subjected to security and maintenance operations by using the nondestructive testing methods. In this field, the Eddy current technique is widely used for evaluating and controlling relevant elements of an aircraft. During our traineeship in the Algerian Airline nondestructive testing edifice, we noticed that the electric conductivity, magnetic permeability and thickness of metal sheets measurements are carried out separately which increases the inspection time. Absolutely, when using inverse algorithms involving artificial intelligence, the measurement can be made simultaneously and rapidly. As stated above, an inversion procedure using the optimization algorithms associated with finite element method is elaborated in the MATLAB environment.

A comparative study between these three methods (GA, SIM, and PSO) for solving the eddy current inversion problem has been proposed in this paper. As a result, we have deduced that FEM-GA and FEM-PSO are very slow in comparison to the FEM-SIM because of the height number of fitness function calculation for each iteration.

On the other hand, to reach a satisfactory precision, the population size has to be increasedto a certain extent since it increases the calculation time. In fact, the FEM-SIM is more privileged because it is faster and its algorithm performance does not change while restarting calculation [17,18].

REFERENCES

[1] G. Cosarinsky, J. Fava, M. Ruch and A. Bonomi, "Material Characterization by Electrical Conductivity Assessment using Impedance Analysis", *Procedia Mater. Sci.*, vol. 9, pp. 156–162, 2015.

[2] J. Garcia-Martin, J. Gomez-Gill and E. Vazquez-Sanchez, "Non-Destructive Techniques based on Eddy Current Testing", *Sensors J.*, vol 11, pp. 2525–2565, Feb. 2011.

[3] Abdou A., Bouchala T., AbdelhadiB.,Guettafi A.,BenoudjitA., "Real-Time Eddy Current Measurement of Aeronautical Construction Material Coating Thickness", *Instrum. Meas. Metrol.*, vol. 18, no. 5, pp. 3–4, Nov. 2019.

[4] X. Ma, A. J. Peyton and Y. Y. Zhaob, "Measurement of the Electrical Conductivity of Open-Celled Aluminum Foam using non-Contact Eddy Current Techniques". *NDT E Int.*, vol. 38, no. 5, pp. 359–367, 2005.

[5] C. V. Dodd and W. E. Deeds, "Analytical Solutions to Eddy-Current Probe-Coil Probe Problems", *J. Appl. Phys.*, vol. 39, no. 6, pp. 2829–2839, Sep. 1968.

[6] T. Bouchala, B. Abdelhadi and A. Benoudjit, "Fast Analytical Modeling of Eddy Current Non-Destructive Testing of Magnetic Material", *J. Nondestruct. Eval.*, vol. 32, no. 3, pp. 294–299, Sept. 2013.

[7] T. Bouchala, B. Abdelhadi and A. Benoudjit, "Novel Coupled Electric Field Method for Defect Characterization in Eddy Current Non-Destructive Testing", *J. Nondestruct. Eval.*, vol. 32, no. 4, pp. 1–11, Sept. 2013.

[8] T. Bouchala, B. Abdelhadi and A. Benoudjit, "New Contactless Eddy Current Non-destructive Methodology of Electric Conductivity Measurement", *J. Nondestruct. Test Eval.*, vol. 30, no. 1, pp. 63–73. Jan. 2015.

[9] T. Bouchala, B. Abdelhadi and A. Benoudjit, "Application of Coupled Electric Field Method for Eddy Current Non-Destructive Inspection of Multilayer Structures", *J. Nondestruct. Eval.*, vol. 30, no. 2, pp. 8–10, March 2015.

[10] D. Vielldent, "Optimisation des Outils en Forgeage a Chaud par Simulation Elément Finis et Méthodes Inverse. Application a des Problèmes Industriels", Thèse de Doctorat, Ecole Nationale Supérieure des Mines de Paris, 1999.

[11] B. Maouche and M. Feliachi, "A Half Analytical Formulation for the Impedance Variation in Axisymmetric Modeling of Eddy Current Non-Destructive Testing", *EPJ Appl. Phys.*, vol. 33, pp. 59-67, Feb. 2006.

[12] B. Maouche, A. Rezak and M. Feliachi, "Semi Analytical Calculation of the Impedance of Differential Sensor for Eddy Current Non-Destructive Testing", *NDT E Int.*, vol. 42, no. 7, pp. 573-580, Oct. 2009.

[13] S. Zerguini, B. Maouche, M. Latreche and M. Feliachi, "A Coupled Fictitious Electric Circuit's Method for Impedance of a Sensor with Ferromagnetic Core Calculation. Application to Eddy Currents Non-Destructive Testing", *EPJ Appl. Phys.*, vol. 48, no. 3, pp. 31202-31207, Dec. 2009.

[14] J. Blitz, *Electrical and Magnetic Methods of Non-Destructive Testing*. New York: Chapman &Hall, 1997.

[15] Y. Yating, D. Pingan and X. Luchuan, "Coil Impedance Calculation of an Eddy Current Sensor by the Finite Element Method", *Russ. J. Nondestruct. Test.*, vol. 44, no. 4. pp. 296–302, April 2008.

[16] V. P. Lunin, "Phenomenological and Algorithmic Method for the Solution of Inverse Problem of Electromagnetic Testing", *Russ. J. Nondestruct. Test.*, vol. 42, no. 6, pp. 353–362, June 2006.

[17] I. Dolapchiev, K. Brandisky and P. Ivanov, "Eddy Current Testing Probe Optimization Using a Parallel Genetic Algorithm", *Serb. J. Electr. Eng.*, vol. 5, no. 1, pp. 39–48, May 2008.

[18] A. Bouzidi, B. Maouche and M. Feliachi, "Pulsed Eddy Current NDE of Groove Dimensions by Inversion with Simplex Method Associated with Coupled Electric Circuits Method", *IEEE Trans. Magn.*, vol. 51, no. 3, pp 55–61, March 2015.