GEOMETRICAL OPTIMIZATION OF SENSORS FOR EDDY CURRENTS NONDESTRUCTIVE TESTING AND EVALUATION

Frédéric Thollon, Noël Burais

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Frédéric THOLLON - Noël BURAIS
CEGELY - URA CNRS 829
Ecole Centrale de Lyon - Dépt. Electrotechnique - BP 163 - 69131 Ecully - France

Abstract **: Design of NDT and NDE sensors is possible by solving Maxwell's relations with FEM or BIM. But the large number of geometrical and electrical parameters of sensor and tested material implies many results that don't give necessarily a well adapted sensor. The authors have used a genetic algorithm for automatic optimization. After having tested this algorithm with analytical solution of Maxwell's relations for cladding thickness measurement, the method has been implemented in Finite Element package and applied to the design of sensor for cracks detection under installed fasteners in aircraft structure.**

I. INTRODUCTION

Eddy currents are widely used for Non Destructive Testing (NDT) and Non Destructive Evaluation (NDE) of conducting structures. Solving Maxwell's relations with 2D or 3D classical numerical methods allows to simulate electromagnetic phenomena and to accurately predict sensors response [1],[2]. But several difficulties are related to the eddy current control method :

- very small variations of sensor response.
- many geometrical and electrical parameters can modify sensors response.
- eddy currents decreasing rapidly in the tested material because of the skin effect, deeper cracks can not be detected.

An optimized sensor must induced the greatest eddy currents density near the crack, in order to obtain the greatest sensor response [8], [9]. This can be done by using adapted finite element package [2] with parameters studies. But the number of physical parameters implies many 2D or 3D calculations, and a lot of results that can not be easily used by the designer for industrial applications, and the sensor is not really optimized.

So, the authors have used and implemented a genetic algorithm in numerical packages in order to automatically obtain the numerical values of geometrical parameters of the optimized sensors.

II. GENETIC ALGORITHM

Genetic algorithms (GA) are search algorithms based on the mechanism of natural selection [3]. They act on a set of artificial creatures that represent design configurations. The set of creatures constitutes a population. Each creature is associated with a value of the objective function we want to maximize. GA uses only this function for optimization, not derivatives. The creatures are coded as a finite length string over a finite alphabet. In our case, binary alphabet (0,1) is used. From a first set of strings, GA generate new creatures in such a way that new individuals perform better than their predecessors. GA uses probabilistic rules such as reproduction, cross-over and mutation. Reproduction is a process in which creatures associated to a high value of objective function have a higher probability to survive. Cross-over and mutation allow to introduce new genetic material and to test new configurations.

A. Reproduction

A new population is generated with the same number of individuals. Let the objective function value associated with the jth individual denoted by f_j, the sum of these values for the whole population by f_{sum}, and the mean value by f_{mean}. We can use several criteria to proceed the reproduction:

- the ratio f_j/f_{sum} is used to construct a weighted roulette wheel where each individual occupies an area on this wheel proportional to this ratio. The roulette wheel is then used to determine the individuals that participate in the next population.
- we can also use the ratio f_j/f_{mean}. We first duplicate each individual (integer part(f_j/f_{mean})) times. We complete the population with the reproduction of each individual with a probability p_{select}:

$$p_{select} = (f_j/f_{mean} - \text{integer part}(f_j/f_{mean})). \tag{1}$$

Regulation of number of copies is especially important in small population. It is common to have a few extraordinary individuals in a population of mediocre individuals. To avoid a premature convergence because the extraordinary individuals would be duplicated too many times, we can scale the objective function before reproduction. For example, linear scaling can be used. The scaled objective function f'_j is expressed as:

$$f'_j = a \times f_j + b \tag{2}$$

with $f'_{mean} = f_{mean}$ and $f'_{max} < f_{max}$.

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a is chosen to limit the influence of extraordinary individuals. Prior to scaling, we can use sigma truncation to eliminate the weakest individuals:

$$f'_j = f_j - (f_{mean} - c\,\sigma) \quad (3)$$

where σ is the standard deviation. The constant c is chosen between 1 and 3. Negative results ($f'_j < 0$) are set to 0. We can then proceed with linear scaling.

B. Cross-over

After reproduction, new creatures can participate in the cross-over process. First, individuals are mated at random. Second, each pair of individuals undergoes crossing process with a probability p_{cross}. If the cross-over is decided, the cross-over position is selected at random. Let l be the length of the individuals and k the cross-over position, two new strings are created by swapping all characters between position k+1 and position l. For example, with k=4:

Before cross-over: $A=a_8a_7a_6a_5|a_4a_3a_2a_1$
$B=b_8b_7b_6b_5|b_4b_3b_2b_1$

After cross-over: $A'=a_8a_7a_6a_5b_4b_3b_2b_1$
$B'=b_8b_7b_6b_5a_4a_3a_2a_1$

C.Mutation

The mutation is the random alteration of each single character of each string with a probability p_{mut}. For example, if the fourth character of bit string A has to be changed, we obtain a new bit string A':

Before mutation: $A=a_8a_7a_6a_5|a_4|a_3a_2a_1$
After mutation: $A'=a_8a_7a_6a_5|a_4|a_3a_2a_1$

D. How does GA work?.

The effect of reproduction, cross-over and mutation on the evolution of the population is explain using the notion of schemata [4]. An extended alphabet (0,1,*) is used where * is the "don't care" character. With this alphabet, we can create schemata. A schemata matches a particular string if at every location a 1 matches a 1, a 0 matches a 0, a * of the schemata matches either in the string. For example, the schemata H=1*1*0 matches 4 strings of length l=5 {(10100),(10110),11100),(11110)}

All schemata are not created equal. Some are more specific than others. To compare difference schemata, two properties are introduced: schemata order and defining length.

The order of a schemata H denoted by o(H) is the number of fixed positions. In the example above o(H)=3.

The defining length denoted by $\delta(H)$ is the distance between the first and the last specific string position. In the example above, $\delta(H) = 5-1 = 4$.

GA process a large quantity of schemata while processing a relatively small quantity of strings.

1)Effect of reproduction: suppose at a given generation G, there are m(H,G) strings that match with the schemata H. If f(H) is the mean value of objective function for all strings that match with H at generation G, the numbers of strings that match with H at generation G+1 is expressed as:

$$m(H,G+1)=m(H,G)\,f(H)/f_{mean}. \quad (4)$$

In these conditions, we can see that above-average schemata number grows.

2)Effect of cross-over: the cross-over survival probability of a schemata may be expressed by the expression:

$$p_{sc} \geq 1 - p_{cross}\frac{\delta(H)}{l-1}. \quad (5)$$

3)Effect of mutation: the probability of surviving mutation is expressed as:

$$p_{sm} \geq (1-o(H))^{pm} \approx 1 - pm\, o(H). \quad (6)$$

4)Expected number of copies: a particular schemata H receives an expected number of copies in the next generation under reproduction, cross-over and mutation as:

$$m(H,t+1) \geq m(H,t)\frac{f(H)}{f_{mean}}\left(1 - p_c\frac{\delta(H)}{l-1} - p_m o(H)\right). \quad (7)$$

As conclusion, we can say that short, low-order, above average schemata number increases in subsequent generations.

E. Implementation.

When we want to optimize an objective function f(x) where x is a real parameter by using GA, we have first to code this parameter. In order that, we define an interval of variation $[x_{min}, x_{max}]$ and a precision p. The number of characters l we need to code is then, for a binary coding, expressed as:

$$l = \text{integer part}\left(\log\left(\frac{x_{max}-x_{min}}{p}+1\right)/\log 2\right)+1. \quad (8)$$

For a multi-parameters function $f(x_1,x_2,...x_n)$, we can simply concatenate each single parameter coding:

$$\text{string} = \underset{l_1 \text{ bits}}{(\text{code}_1)}\ \underset{l_2 \text{ bits}}{(\text{code}_2)} \dots \underset{l_n \text{ bits}}{(\text{code}_n)}.$$

As GA works on schemata, the order in which we concatenate each parameter coding is not important.

After the generation of a new population, the sub strings corresponding to each parameter are decoded in order to calculate the new values of objective function.

GA creates new values of parameters that are in their specified interval. But, GA doesn't take into account constraints that link parameters. Therefore, after decoding, we have to introduce these constraints before calculating objective function. We can use following methods:

- we can always calculate objective function: we associate a penalty function to objective function with all constraints violations.
- we can't always calculate objective function: we define the most important parameters. The value of other parameters are calculated by taking into account constraints. We apply then a penalty function to objective function.

Fig. 1 shows a flow-chart that represents an implementation of GA.

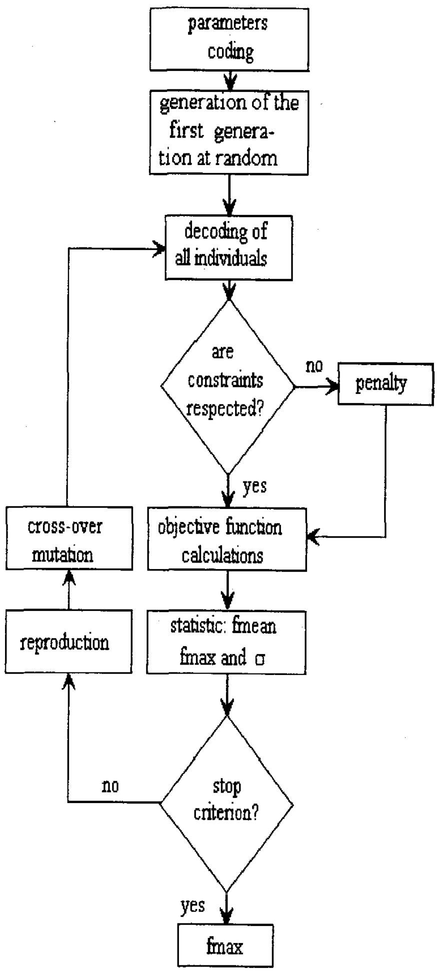

Fig. 1. GA implementation

III. Application to Non Destructive Evaluation : Cladding Thickness Measurement

The genetic algorithm is used to design cladding thickness measurement system. In this case, geometry is simple and axisymmetric (coil upon two materials), so that the governing classical magneto dynamic equation has analytical solution [5] (Fig. 2).

The algorithm is tested with two geometrical parameters of the coil (radius R , width W) and the frequency f of current that supplies the coil in order to obtain adapted impedance variation for the cladding thickness measurement.

The variation range of T is known $[0, T_{max}]$. The turns number of the coil is imposed. We want to obtain:

- impedance variations as important as possible.
- impedance variations as linear as possible.

We already know that we can't have the largest variations and the best linearity together. So, we have to find an objective function that takes into account the variations rate and the linearity with factors allowing to favour either one of these two quantities.

For a set of values of R, W and f, the impedance Z is calculated according to the thickness T. A linear regression is performed with obtained values. The linearized impedance can be expressed as:

$$Z_L = A \times T + B. \tag{9}$$

A represents the value of the mean slope of the impedance variations. The regression quality is defined with the cross correlation coefficient between Z and Z_L:

$$CORR = cross\ correlation(Z, Z_L). \tag{10}$$

In these conditions, an objective function is defined by:

$$fobj = |A| + \frac{k}{1 - CORR} \tag{11}$$

where k is a coefficient chosen in function of variations of A and CORR. Furthermore, to limit CORR influence, especially when it is close to 1, we impose the following constraint:

$$if\ CORR > CORRMAX\ then\ CORR = CORRMAX \tag{12}$$

For example, for a magnetic sheet (μ_r=100, σ=10^5S/m) and a nonmagnetic cladding (σ= 17 10^6S/m), for a 9 mm^2 cross section coil, the obtained solution with k=20, CORRMAX=0.99, a 50 individuals population and 20 generations is showed in table 1.

This calculation needs one hour on an HP9000 series 715.

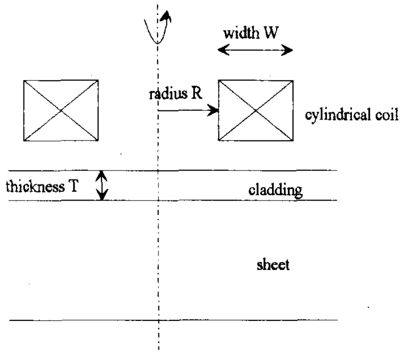

Fig.2. thickness measurement

A calculation with k=30 doesn't allow to obtain a good slope. Another calculation with k=10 gives too much importance to the slope and it is very difficult to obtain the wished cross correlation coefficient.

To verify that the solution is in the neighbourhood of the maximum, calculations are done for parameters variations of 10% around the optimal values. Table 2 gives the results.

We can see that there is a good agreement between the results and our criteria.

Moreover, we may conclude that frequency and radius are the most important parameters for the solution quality.

Fig. 3 shows impedance variations according to the thickness for three frequencies.

As conclusion, we may say that we obtained a design that corresponds with the criteria used to establish the objective function. The quality of the solution is very sensitive to the values of the coefficients (in our case k and CORRMAX) we introduce in the objective function. The most important part of work in such a problem is the choice of a "good" objective function.

IV. Coupling Finite Element Method with GA

A. Description of simulation package

FISSURE is a general interactive package which allows the modelling of phenomena in Non Destructive Testing (NDT) and Non Destructive Evaluation (NDE) by electromagnetic methods : Magnetic Field Leakage, DC or AC Potential Drop, and Eddy Currents.

This package can be used particularly for the following applications in NDT or NDE :

- knowledge of electromagnetic phenomena in order to develop and optimize sensors,
- simulation of sensor responses for electromagnetic, geometrical and electrical parameters of both material to control and sensor, in order to identify and quantify defects in industrial controls.

FISSURE solves various systems of equations obtained from Maxwell's relations for linear 2D or 3D axisymmetric structures by Finite Elements Method (FEM). Particularly,

TABLE 1

Optimal solution

fopt	Ropt	Wopt	A	CORR
17600Hz	17.9mm	8.8mm	-95.9 Ω/m	0.99

TABLE 2

Variations around the maximum

	CORR	A
optimal solution	0.99	-95.92
fopt-10%	0.9927	-82.24
fopt+10%	0.9869	-109.66
Ropt-10%	0.9919	-83.20
Ropt+10%	0.9881	-108.6
Wopt-10%	0.9900	-92.1
Wopt+10%	0.9893	-97.2

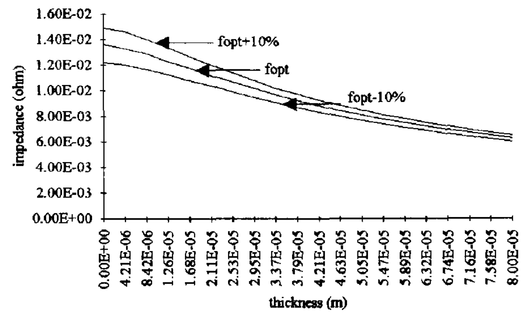

Fig.3. frequency influence

for eddy currents NDT systems, the following classical linear magneto dynamic equation is solved for sinusoidal or transient signal :

$$1/\mu.\Delta A - \sigma.\delta A/\delta t = - Jex \quad (13)$$

where Jex is the current density in the coil.

FISSURE is adapted to simulate automatically sensor responses for the following parameters variations:

- frequency for sinusoidal signal, or harmonic components for transient signal.
- sensor displacement.
- defect sizes and physical properties.
- probe structure (absolute or differential measurement, length between excitation and measurement coils).

Different sensors values can be calculated :

- active and reactive powers in all parts of the studied system.
- eddy currents density.
- flux density.
- flux through a very thin or classical coil (fixed or moving coil).

- impedance.

Very small variations of electromagnetic phenomena in NDT imply special package structure. In order to minimize the influence of finite elements mesh on the results (sensor response), mesh of the geometry is once automatically made taking into account the possible modifications of the simulated geometry. For example, if radius variation of exciting coil has to be simulated, the study domain includes all positions of the area corresponding to the coil. At one step, given coil radius is simulated by applying physical properties (permeability, conductivity, current density) of the coil to corresponding triangles of the mesh, and properties of air to other concerned triangles. All calculations are twice performed : with and without defect, in order to obtain absolute and differential signal. This last value is essential in NDT particularly for characterising the sensor performances.

B. Adaptation of FEM Package to Optimization

Genetic algorithm has been successfully implemented with BEM and FEM package for optimization of electrostatic devices [6],[7].

From these experiences, we have decided to introduce GA in FEM package FISSURE in the purpose to optimize magneto dynamic devices, more particularly eddy current sensors.

For geometrical optimization of one part of the eddy current NDT system (coil for example), a specific area is defined in study domain and subdivided in several little media (Fig. 4). Optimization process can impose on each of these media, adapted physical properties in order to simulate the absence or the presence of the part. So, geometrical modifications of the studied part in this limited area can be simulated. Mesh is made once taking into account all media included in the optimization areas. This method implies a further number of triangles in the mesh but minimizes calculation errors.

Various electromagnetic values can be calculated in optimization process: flux density, power losses, eddy currents density, flux through an unchanging area, and flux through a moving area (optimization area).

In the package, for each step of the optimization process, a set of geometrical and frequency parameters is automatically imposed and FEM resolution is performed. From the electromagnetic calculated values, the objective function value is computed and analysed for each step. Optimization process is performed for the defined number of individuals and generations.

One of the interests of the genetic method is that the main part of the resolution FEM package has not to be modified when genetic algorithm is introduced. The performances of this package are tested with eddy currents non destructive testing in aircraft structure.

V. Application to Non Destructive Testing: Optimization of a Eddy Current Probe Used to Detect Flaws in Aeronautic Structures

This part is concerned with eddy current inspection of aircraft structures during maintenance periods. The structure to control is showed Fig.4.

All materials are nonmagnetic, the metallic sheet has an important conductivity.

In such a structure, cracks can occur along the rivet at important depth (> 5mm). The presence of a defect induces a very low level signal. The first step to design a "good" probe is therefore to optimize the coil and the current that create eddy current in order to have a "flaw signal" as important as possible. The parameters to optimize, for a given coil turns number, are:

- coil radius
- coil width
- frequency of supply current.

The objective function is expressed as:

$$fobj = \left| \frac{\textit{flux density without flaw} - \textit{flux density with flaw}}{\textit{turns number}} \right|$$

where the flux density is calculated in a particular point.

The optimization of the coil is undertaken by creating an optimization zone. This zone is divided into elements which dimensions depend on cross section of conductor used to do the coil. A particular outline is obtained by assigning a current density J to particular elements, a null current density to the others. We have to take into account following constraints:

- the coil must have a rectangular cross-section. Therefore, the number n_h of elements along the horizontal is first determined. Then, we calculate the number n_v along the vertical according to the desired turns number. The effective turns number is calculated as $n_r = n_v \times n_h$.
- the coil must be in the optimization zone. If GA gives values that don't agree with this zone, we can, for example:
  - keep radius value.
  - calculate width according to the constraint.
  - apply to the objective function a penalty coefficient to decrease the surviving probability of this solution.

Fig.5 and Fig.6 show the "best" coils obtained respectively for 5mm deep and 10mm deep cracks. The optimal frequencies are respectively 1100Hz and 273Hz. These results are in agreement with well known properties of eddy current inspection. The deeper the flaw is, the lower the eddy current operating frequency needs to be, the larger the coil radius also needs to be. We know also we have to use pancake coil to detect deep cracks.

A probe was earlier designed without using automatic optimization. Table 3 shows the sensitivity of the different coils and the improvement due to the optimization.

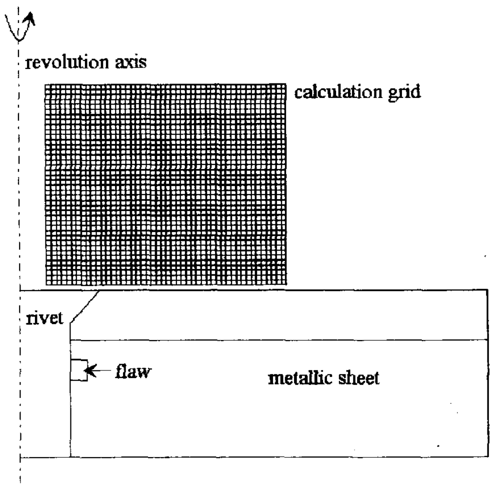

Fig.4. riveted assembly

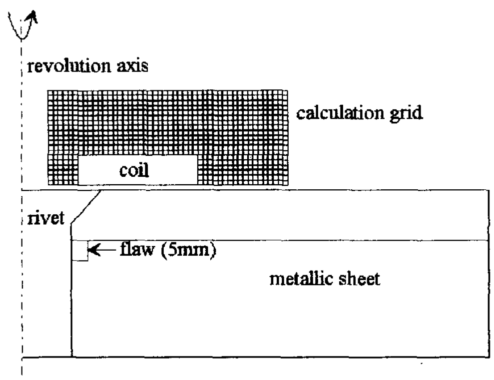

Fig. 5. optimal coil for 5mm depth flaw

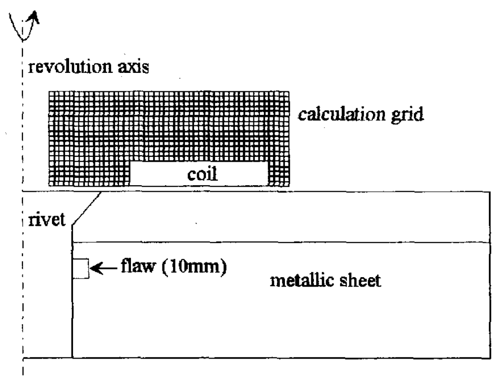

Fig.6. optimal coil for 10mm depth flaw

TABLE 3

COIL SENSITIVITY (Ω/Aturns)

	5mm deep flaw	10mm deep flaw
existing coil	$4.38\ 10^{-8}$	$1.50\ 10^{-9}$
optimized coil	$4.91\ 10^{-8}$	$2.55\ 10^{-9}$
improvement	12%	70%

VI. CONCLUSION

A genetic algorithm has been implemented in FEM electromagnetic package and applied to the design of eddy currents NDE and NDT sensors. The first results show that this method is adapted to industrial applications. Indeed, geometrical parameters of the sensors and working frequency are automatically obtained, and allow to obtain more effective sensors than those already existing. But, with this genetic method, we are not sure to have the best sensors, and further works have to be performed to improve this method. The main advantage of this method is its easy implementation. Particularly, the resolution FEM package has not to be modified. The only work of the user is to write few code lines in order to define parameters to optimize, the objective function and the constraints. The package FISSURE can be quickly applied to others eddy currents applications as induction heating. More generally, this package can be adapted with few modifications to the optimization of various electromagnetic systems.

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