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Eddy Current Testing Probe Optimization Using a Parallel Genetic Algorithm

Ivaylo Dolapchiev[1] , Kostadin Brandisky[2], Petar Ivanov[3]

Abstract: This paper uses the developed parallel version of Michalewicz's Genocop III, Genetic Algorithm (GA) searching technique to optimize the coil geometry of an eddy current non-destructive testing probe (ECTP). The electromagnetic field is computed using FEMM 2D finite element code. The aim of this optimization was to determine coil dimensions and positions that improve ECTP sensitivity to physical properties of the tested devices.

Keywords: ECTP optimization, Inverse problem, Genetic algorithm, Finite element method.

1 Introduction

Classical eddy current non-destructive testing methods are used to determine the physical properties and surface inhomogeneities of conductive materials. The transformer type probes consist of a ferrite core, coaxially placed inside two pancake coils. One of the coils is energized by an AC current source and excites the electro-magnetic field. The induced eddy currents spread in the surface layer of the tested material. At each position of the probe, the magnitude and the density of the currents depend on local properties and homogeneities of the specimen. Variation of eddy current densities cause changes in the field distribution, that brings alteration in the voltage, induced in the second probe's coil. These alterations correspond to changes in the physical properties of the examined specimen.

One of the most important defects of these probes is their strongly nonlinear characteristic and weak sensitivity towards examined specimen characteristics. Analytical investigation of the influences of coil geometry on the probe sensitivity [1] give only rough recommendations on coil dimensions and positions.

This work uses a searching technique based on GA to optimize a transformer type ECTP. The optimization aims to obtain a probe with better

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[1] Technical University of Sofia, Kliment Ohridski 8, Sofia 1000, Bulgaria, E-mail: ivailodo@tu-sofia.bg

[2] Technical University of Sofia, Kliment Ohridski 8, Sofia 1000, Bulgaria, E-mail: kbran@tu-sofia.bg

[3] Technical University of Sofia, Kliment Ohridski 8, Sofia 1000, Bulgaria, E-mail: pniv@abv.bg

sensitivity to the changes of physical properties and dimensions in the tested materials.

2 Ectp Optimization Problem

The main goal of ECTP design is to obtain a probe featuring good sensitivity and minimal volume. This could be achieved by optimizing coil dimensions and positions, subject to previously imposed restrictions on the probe volume. During optimization sensitivity of the ECTP has to be evaluated in a wide range of specimen conductivity.

The conductive materials, subjected to eddy current testing, caused changes in the components Ur and Ui of the induced voltage in the probe's pickup coil. In order to take into consideration most peculiarities of the real ECTP, the induced voltage was obtained using a numerical method for magnetic field computation. The finite element method is used for calculation of Ur and Ui for different conductivity of the specimen. The problem is solved using FEMM [2] software code and the model region is given in Fig. 1.

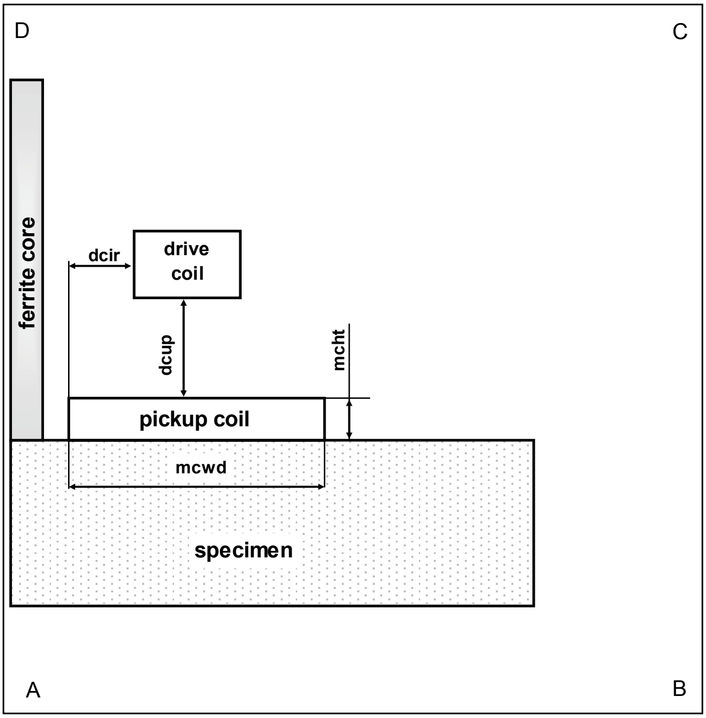

Fig. 1 – ECTP *model region.*

Computations were done with the following simplifications:

- The electromagnetic field is considered two dimensional and axis-symmetric;
- The field attenuates entirely at the boundaries of the ABCD region;
- All used materials are linear and homogeneous.

The problem is solved at $f = 15\,\text{kHz}$ excitation frequency, and magnetic permeability of the core of $\mu_r = 40$. The magnetic flux in the model is driven by the current density $J \cong 0.91\,\text{MA/m}^2$. Calculations were done for 11 different conductivities of the specimen uniformly distributed in the range between 5MS/m and 55MS/m. The goal of optimization was to obtain an ECTP having good sensitivity to the specimen conductivity changes, by changing the size of the pickup coil and position of the driving coil.

3 Optimization Using Parallel GA

Shape optimization of electromagnetic devices is an electromagnetic inverse problem that is usually solved by application of the GA searching technique. The presented optimization uses the developed parallel version of the Michalewicz's Genocop III algorithm [3].

In general GA searches model parameters ensuring the maximum of an objective function *OF*. This function corresponds to the optimization goal, and represents a sum of changes in components of the induced voltage, at different specimen conductivities:

$$OF = \sum_{\sigma=1}^{10} \sqrt{\left(Ur_{\sigma+1} - Ur_{\sigma}\right)^2 + \left(Ui_{\sigma+1} - Ui_{\sigma}\right)^2} \tag{1}$$

The *OF* (1) is maximized by varying the dimensions of the pickup coil, *pc-wd* and *pc-ht* and the position of the driving coil – *dc-ir* and *dc-up*. The parameters are modified inside the limits shown in **Table 1**:

Table 1

Parameters and boundaries.

PARAMETER		LIMITS	
name	Dimension	min	max
pc-wd	mm	2	10
pc-ht	mm	1	3
dc-ir	mm	0	10
dc-up	mm	0	10

The GA started with a randomly generated initial population of 70 individuals. The next generations had a population size of 35. The genetic process was extended up to 100 generations. All genetic operators were used with equal probability of operation of $P_o = 5.71\%$.

4 Results

The optimization was accomplished on a computer cluster of 16 PC, based on AMD Athlon XP 2500+ CPU with 512MB RAM. Client computers and server - ASUS A3E-5003 laptop were connected by a 100 Mbit/s Ethernet network and worked under Windows XP Pro SP2 OS.

The parallel GA started with a random generated initial population, and found the optimal solution at the 51^{-th} generation. During optimization 3570 *OF* were calculated, and the computation lasted 6h 35 min. Some results for the values of model parameters and corresponding *OF*, are collected in **Table 2**.

The probe ECTP # 1 has parameter values that cause maximum of the *OF*. Most conventional probes of this type are designed on the base of principles that lead to parameters and *OF* values similar to the values for ECTP # 2. The last column of the table contains information for the probe with bad *OF*. These results are shown only to illustrate the strong dependence of *OF* on the chosen coils' parameters.

Table 2
ECTP *parameters.*

VARIABLES		VALUES		
name	Dim	ECTP # 1	ECTP # 2	ECTP # 3
OF	V	16.55	13.19	3.11
pc-wd	mm	9.44	7.55	9.85
pc-ht	mm	1.03	1.19	2.26
dc- ir	mm	5.96	5.56	2.63
dc-up	mm	0.12	0.58	9.59

In order to examine the potential of the optimized probe, several numerical simulations of non-destructive testing situations were conducted. Both probes - optimized ECTP # 1, and conventional ECTP # 2 were placed in identical situations. Changes in their induced voltages *dU* were computed, and the sensitivity improvement *Sn_Im* of the ECTP # 1 compared to the conventional probe ECTP # 2 was determined.

The conductivity of non-ferromagnetic specimens is usually measured by means of eddy current NDT methods. This process is simulated using the same numerical model, Fig. 1. The changes in the induced voltages, in relation to their values for the specimen with 5MS/m conductivity, are shown in Fig. 2. The sensitivity improvement of the optimized probe is better than 25% in the examined region of conductivity changes.

Thicknesses of nonconductive coatings, placed over non-ferromagnetic specimens are usually tested by similar eddy current testing equipment. The numerical model that simulates the measuring process is based on the model in Fig. 1. Here the thickness of the coating is shaped by changing the distance between the probe and the specimen. The conductivity of the specimen is accepted to be 30MS/m. Changes in the induced voltages were computed in relation to their values for a non-coated specimen, Fig. 3. Comparing the output characteristics of both probes, the sensitivity improvement of ECTP #1 was determined. It was above 22% for the examined thicknesses of nonconductive coatings.

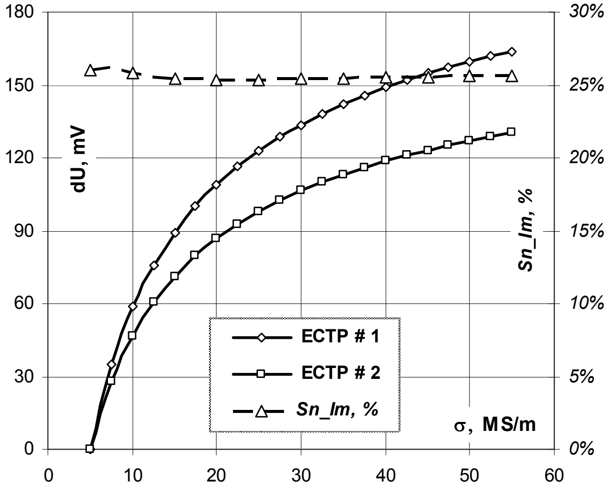

Fig. 2 – *Probe characteristics in relation to the specimen conductivity.*

Surface cracks in conductive devices are usually identified and measured using eddy current NDT methods. To check the potential of the optimized probe in the field of crack identification, another numerical model was constructed, Fig. 4. The investigation used a specimen with a surface crack, whose width, depth and position "X-pos" were subject to change. The specimen was made of aluminium with 30MS/m conductivity. The driving coil of the probe was energized by the same source as described in Fig. 1.

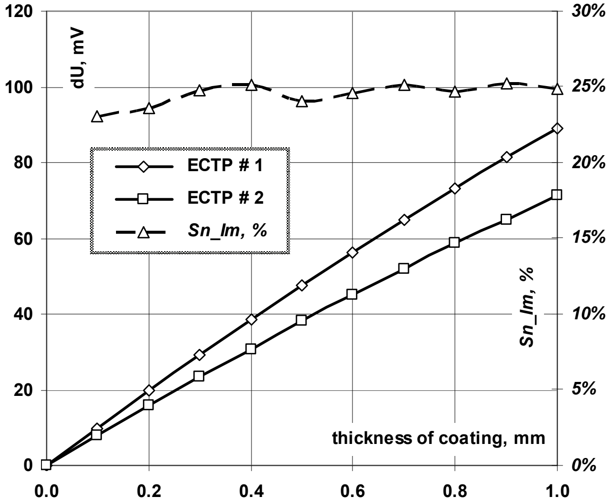

Fig. 3 – *Probe characteristics in relation to the thickness of specimen coating.*

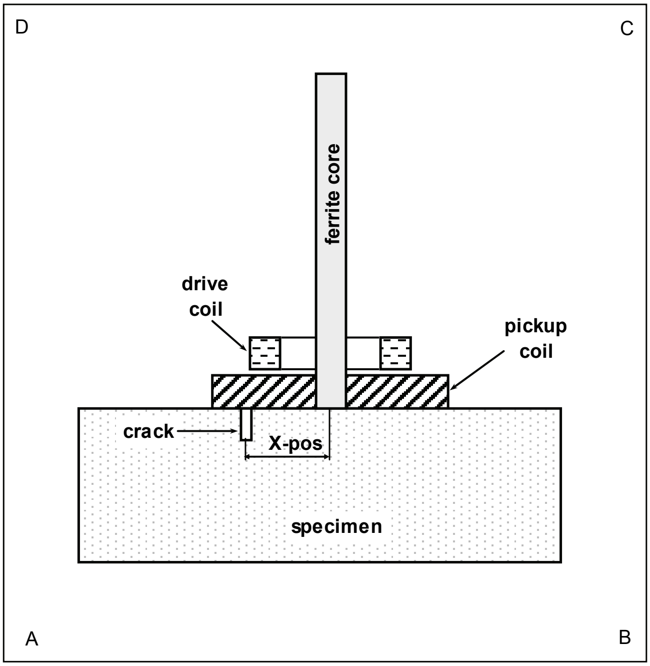

Fig. 4 – ECTP *and cracked specimen model region.*

This model was used to examine the influence of crack dimensions and position on the induced voltage in the probe's pick up coil. Several numerical simulations were conducted changing crack width and depth. At each crack position the values of the induced voltage were calculated. The obtained results were compared to the voltage, induced in the probe, placed on a specimen without a crack. Calculations were conducted for the optimized ECTP # 1, and for the conventional probe ECTP # 2. Variations in the induced voltage in relation to crack dimensions and position for both probes are summarized in Figs. 5 and 6.

The curves in Fig. 5 and Fig. 6 represent the output characteristics of the optimized (#1) and the conventional (#2) probes. In the first chart, the depth of the crack is changed from $d1 = 1\,\text{mm}$ to $d2 = 2\,\text{mm}$, keeping the width equal to $w3 = 3\,\text{mm}$. On the next figure, the crack depth is accepted to be $d2 = 2\,\text{mm}$, and its width is modified from $w2 = 2\,\text{mm}$ to $w1 = 1\,\text{mm}$. In both investigations the optimized probe offers better sensitivity to changes in crack dimensions.

By comparing probe potentials one could generalize that their output voltage increases both with crack width and depth. Not one of the probes has a characteristic that allows identification of only one crack dimension.

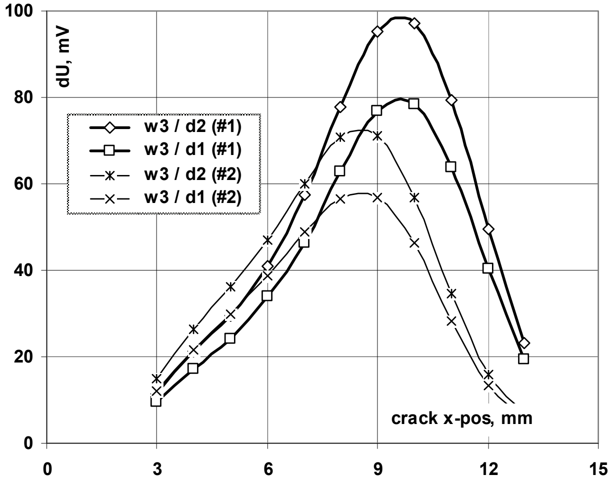

Fig. 5 – *Changes in the induced voltage in relation to crack depth.*

Both probes were placed on identical specimens and used the same current source, but the differences in their geometry transposed the peaks in their characteristics. In order to compare their potentials to the crack dimension identification, these characteristics are represented in regard to the relative crack position. The zero values on the *x*-axis in this presentation point to the peak in the characteristics.

By comparing the induced voltages in both probes, the sensitivity improvement curves of the optimized probe, Fig. 7 and Fig. 8, were constructed.

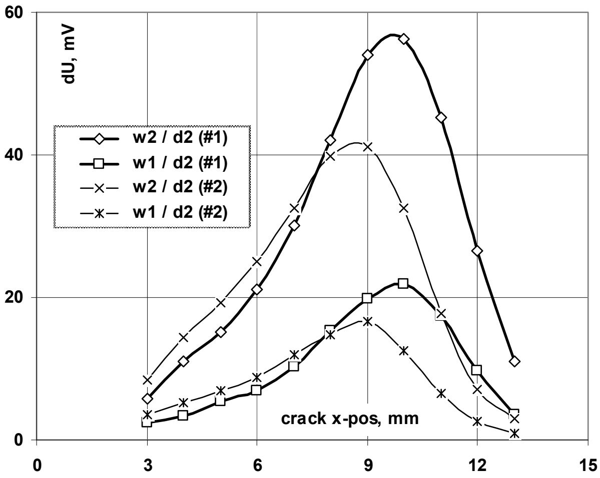

Fig. 6 – *Changes in the induced voltage in relation to crack width.*

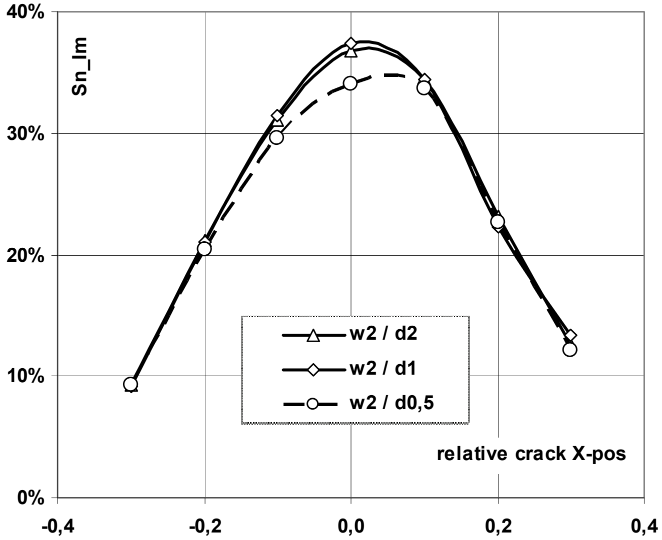

Fig. 7 – *Sensitivity improvement in relation to crack depth.*

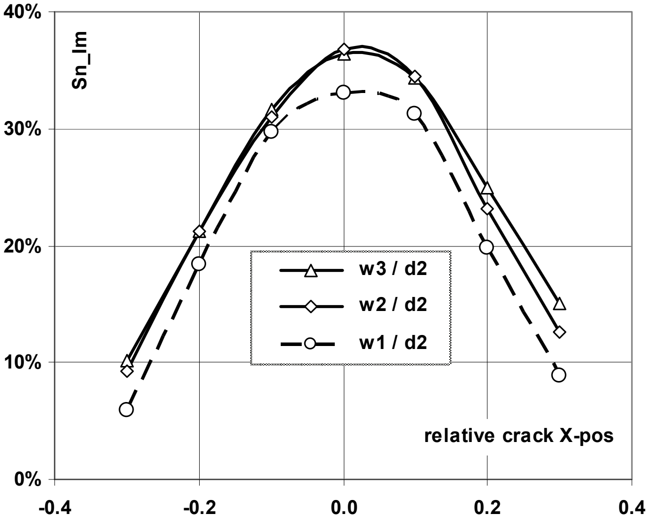

Fig. 8 – *Sensitivity improvement in relation to crack width.*

The conducted additional investigation using cracks with a width of $w3 = 3\,\text{mm}$ and depth $d0{,}5 = 0.5\,\text{mm}$ enabled the conclusion that the optimized probe offers more than 25% improvement of sensitivity in comparison to the conventional one.

5 Conclusion

In this paper parallel GA and finite element methods were combined to solve an ECTP optimization problem. Because the solution of the forward problem is performed by a CAD system, parallel GA computation enabled accelerating of calculations more than 14 times.

The obtained solution of the optimization problem probe ECTP #1 was tested numerically in relation to conductivity and coating thickness measurements, and also surface crack identification.

The sensitivity of ECTP #1 was computed, comparing its output voltage changes to the voltage changes in the pick up coil of a conventional probe of the same type – ECTP #2. The comparison was conducted numerically using appropriate models for each probe and specimen. Every ECTP used identical current sources, coils with an equal number of turns and a conductive non-ferromagnetic specimen with one and the same thickness.

The conducted numerical investigations of the influence of the specimen conductivity and thickness of the non-ferromagnetic coating on voltage changes in the optimized ECTP show, that this probe offers more than 22% growth in sensitivity. This is due to the closest position of the excitation coil to the specimen, and to the optimized dimensions of the pick up coil.

Verification of the probe's potentials in the field of crack identification was conducted using relatively big defects. Their width varied from 50% up to 150% of the width of the driving coil. In this region ECTP #1 offered more than 30% growth of sensitivity in respect to ECTP #2.

To examine the influence of crack depth to the optimized probe sensitivity several numerical simulations were conducted. Depths of the used defects were chosen to be less than or equal to the depth of eddy current penetration. The obtained results show that sensitivity improvement of ECTP #1 was better than 30% again.

In spite of the received good results for ECTP # 1 sensitivity, one couldn't conclude that the obtained geometry is the best possible for the considered ECTP type. This is only the probe with the most suitable geometry among the examined variants.

6 References

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