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# RECONSTRUCTION OF DEFECT SIZE AND SHAPE IN EDDY-CURRENT TESTING USING BENCHMARK PROBLEMS VALIDATION AND NEURAL NETWORK APPROACH

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## ABSTRACT

The benchmark problems in eddy-current nondestructive evaluation (EC-NDE) are based on careful measures of the change in coil impedance as a function of circular air cored coil position which is scanned along the axis of machined slot by electrodischarge in aluminum plate. Tow benchmark problems (TEAM workshop n° 15-1, and JSAEM n° 2-5) are presented to validate and verify ANSYS Maxwell 3D-resolution of defect size and shape using electromagnetic formulation. In order to provide a challenge for current theoretical models, slots of rectangular, elliptical, slope and triangular profiles are considered. The final impedance data can be directly used to verify theoretical inversion algorithms.

**Keywords:** Eddy-current testing; benchmark problems; flaw sizing; finite element method, inverse problem; neural network.

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## 1. INTRODUCTION

Eddy-current nondestructive evaluation is widely used to detect cracks, corrosion, and other defects in metallic structures. The basic setup in eddy current testing (ECT) comprises a probe coil driven by an alternating current, a conductive piece under test and a rather small defect/discontinuity usually in the form of a narrow crack. The purpose of the inspection is to reveal the presence and characteristics of the defect through the impedance variation of the coil when it is scanned over the testpiece. The presence of defects such as fatigue cracks or corrosion perturb the eddy-current distribution in the vicinity of this defect. This perturbation leads to a change in the induced magnetic field and hence induced coil voltage that signals the presence of a flaw.

An eddy-current configuration modelling cannot be obtained analytically and requires the use of 3D numerical methods, among them, the finite element method (FEM). Regarding FEM, modeling of eddy-current evaluation is quite challenging since: (i) it is a multi-scale problem, i.e. the defect area constitutes a small part of the solution domain and the field perturbations and defect signals are weak compared to the ones produced by the coil and the conductor, and (ii) thin areas arising from narrow cracks or small lift-offs are usually present and affect the mesh quality [1]. Integral equation methods are also commonly used, but the need for dedicated Green's functions with analytical expressions that correspond to the specific conductor geometries limit their scope.

All solution methods and available codes require validation which is usually performed by comparing theoretical results to precision measurements taken from well prepared experiments [2-3]. Over the past years, several experimental data-sets have been presented in the literature including the TEAM Workshop n° 15-1 and JSAEM n° 2-5 problems.

The aim of the present work is to compare and validate the numerical results to those given by the Team Workshop Benchmark problems, then final impedance data and experimental parameters can be directly used to verify theoretical inversion algorithms of defect size and defect shape in eddy current NDE.

The determination of an unknown defect size and shape from measurements of eddy-current probe response is an inverse problem, and requires as a prerequisite, the solution to the forward problem of calculating coil response for a defect of known shape and size. The forward problem has been studied extensively over recent years and this has led to theoretical models which are capable of predicting the change in coil impedance due to a defect of known dimensions. In order for these models to be verified, a benchmark experiment was performed [4].

Numerical techniques are now being developed for inverting measurements of eddy-current coil impedance in order to determine the size and reconstruct the profiles of planar defects in conducting materials [5-6]. As before, and to test these techniques, precise experimental measurements are required.

The benchmark problems are based on careful measurements of the coil impedance change as a function of frequency and coil position for an air-cored coil which is scanned along the axis of a series of narrow electrodischarge machined slots in thick conductive plate [7]. The geometry selected for the benchmark problems was inspired by the practical inspection problem of eddy-current detection of a defect initiating and growing in a conductive plate, this configuration is an ideal benchmark experiment because of its simple geometry.

Results are presented for four slots: rectangular, elliptical, slope and triangular profiles, and are designed to test inversion algorithms. TEAM Workshop n° 15-1 and JSAEM n° 2-5 benchmark problems are provided for the four defect classes so that these problems can be used for verification of the forward calculations and refinement of the theoretical inversion algorithm, also these problems provide a common basis for comparing the relative merits (speed, accuracy, computational efficiency) of numerical inversion methods.

## 2. FORMULATION

The forward problem typically consists in the determination of the coil impedance variation. A circular air-cored coil is moved along the rectangular slot in a conductive part. Both frequency and lift-off are fixed. The objective is to compute the coil impedance variation (compared to its value over an unflawed part of the plate) as a function of coil position.

The eddy-current problem can be described mathematically using the following partial differential equation in terms of magnetic vector potential and electric scalar potential [8, 9].

$$rot\left(\frac{1}{\text{«}}\,rot\left(\vec{A}\right)\right) = -\left(j\pm\mu\,\vec{A} + \overrightarrow{gradv}\right) + \overrightarrow{J_S} \qquad (1)$$

$\vec{A}$ represents the magnetic vector potential, $v$ denotes the electrical scalar potential, $j$ denotes the imaginary unit, µ denotes the angular frequency of the excitation current $(rad / s)$, « denotes the magnetic permeability of the media involved $(H / m)$, ± denotes the electrical conductivity $(S / m)$ and $\overrightarrow{J_S}$ denotes the current density $(A / m^2)$.

The real and imaginary parts of the coil impedance are determined by using the magnetic energy and the power losses, respectively. Both are deduced from the finite element simulation results [9].

$$Z = R + jL\mu = \frac{1}{I_{eff}^{2}}\left(P_j + j2\mu W_m\right) \qquad (2)$$

$I_{eff}$ denotes the excitation current through the sensor.

## 3. VALIDATION RESULTS

### 3.1. Benchmark Problems validation

The benchmark problems TEAM Workshop 15–1 [4] and JSAEM 2–5 have been considered in order to validate the previously developed model. The experimental arrangement is shown schematically in Fig. 1.

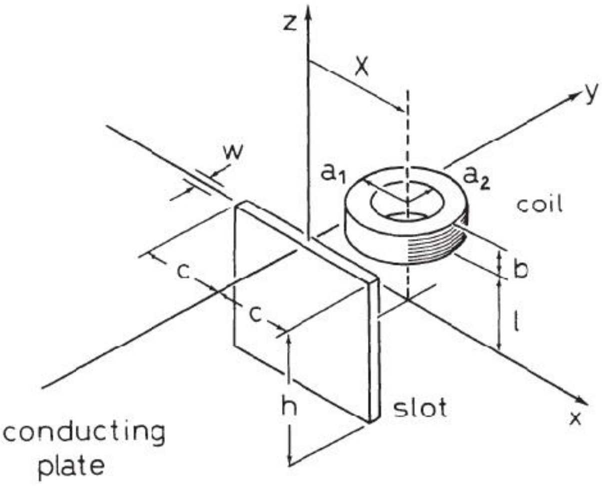


**Fig.1.** Schematic configuration for the benchmark experiment

A circular air-cored coil is scanned, parallel to the *x-axis*, along the length of a rectangular slot in aluminum plate. Both, the frequency and the coil lift-off are fixed, and $\Delta Z = Z_f - Z_0$ is measured as a function of coil-center position. The parameters for these test experiments are listed in Table 1.

$Z_f$ is the probe impedance in the presence of the crack and $Z_0$ is the probe impedance without crack.

**Table 1.** Geometric and physical parameters of the benchmark problems

| | **TEAM 15-1** | **JSAEM 2-5** |
|---|---|---|
| | **Probe** | |
| **Inner radius (mm)** | 6.15 | 0.6 |
| **Outer radius (mm)** | 12.4 | 1.6 |
| **Length (mm)** | 6.15 | 0.8 |
| **Relative permeability** | 1 | 1 |
| **Number of turns** | 3790 | 140 |
| **Lift-off (mm)** | 0.88 | 1 |
| **Frequency (Hz)** | 900 | $150*10^3$ |
| | **Plate** | |
| **Conductivity (S/m)** | $30.6*10^6$ | $10^6$ |
| **Thickness (mm)** | 12.22 | 1.25 |
| | **Crack** | |
| **Length (mm)** | 12.6 | 10 |
| **Depth (mm)** | 5 | 0.75 |
| **Width (mm)** | 0.28 | 0.21 |

The advantage of these benchmarks is that the crack width is very small compared to the other dimensions, which are favorable configurations for the validation of the fine defects model.

The objective of this section is to compute the change of the coil impedance as a function of coil position, and to validate the previously developed model by comparing the results obtained by this one with experimental data on academic benchmark configurations. This is to be done for each problem.

Figs. 2 and 3 show the resistance and the reactance variations of the probe as a function of the probe position along the crack length for the TEAM n° 15-1 and JSAEM n° 2-5 problems, respectively. The crack is centered at $x = 0$. A good agreement is obtained between the numerical and the experimental results.

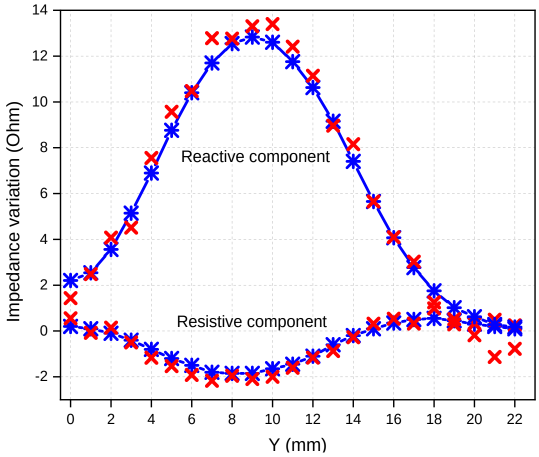


**Fig.2.** Variation of the probe impedance (TEAM problem): FEM simulation ($\times$), and experimentation ($* -$)

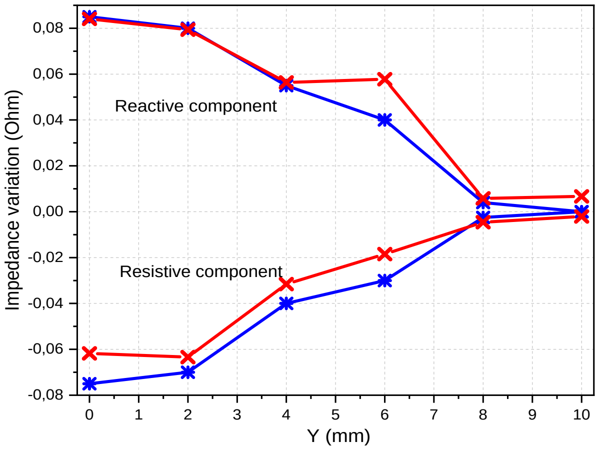


**Fig.3.** Variation of the probe impedance (JSAEM problem): FEM simulation ($\times -$), and experimentation ($* -$)

### 3.2. Flaw of different dimensions problem

The considered problem is a rectangular flawed part scanned by a circular coil containing 5 straight slots of different geometric parameters (length and depth); the slots are perpendicular to the sample's surface.

Figs. 4 and 5 show the eddy current signals, i.e., the variations of the resistance and reactance of the sensor. These signals constitute the signature of the slot.

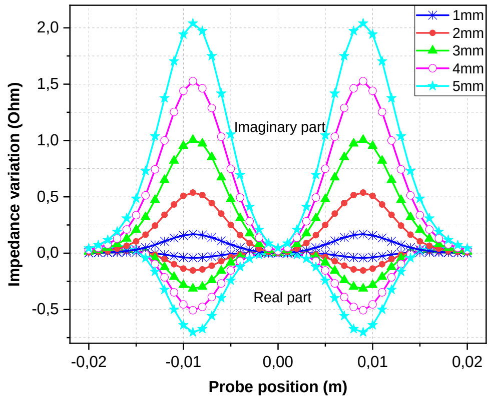


**Fig.4.** Impedance variation as a function of the probe position for different crack lengths of the same thickness (0.20 mm) and depth (2 mm)

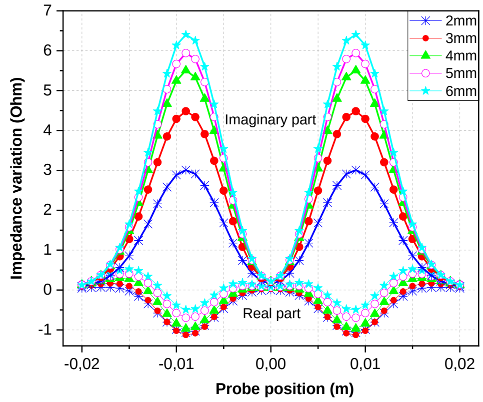


**Fig.5.** Impedance variation as a function of the probe position for different crack depths of the same thickness (0.20 mm) and length (7 mm)

The effect of the crack length and depth on the eddy-current (EC)signals is very apparent. We can therefore conclude that, for thin cracks, the EC signal strongly depends on the length and depth of the crack.

### 3.3. Flaw of different shapes problem

By adjusting the depth variation, keeping the same length and the same width of the crack, slots of four shapes shown in Fig. 6 are considered for the FEM simulation.

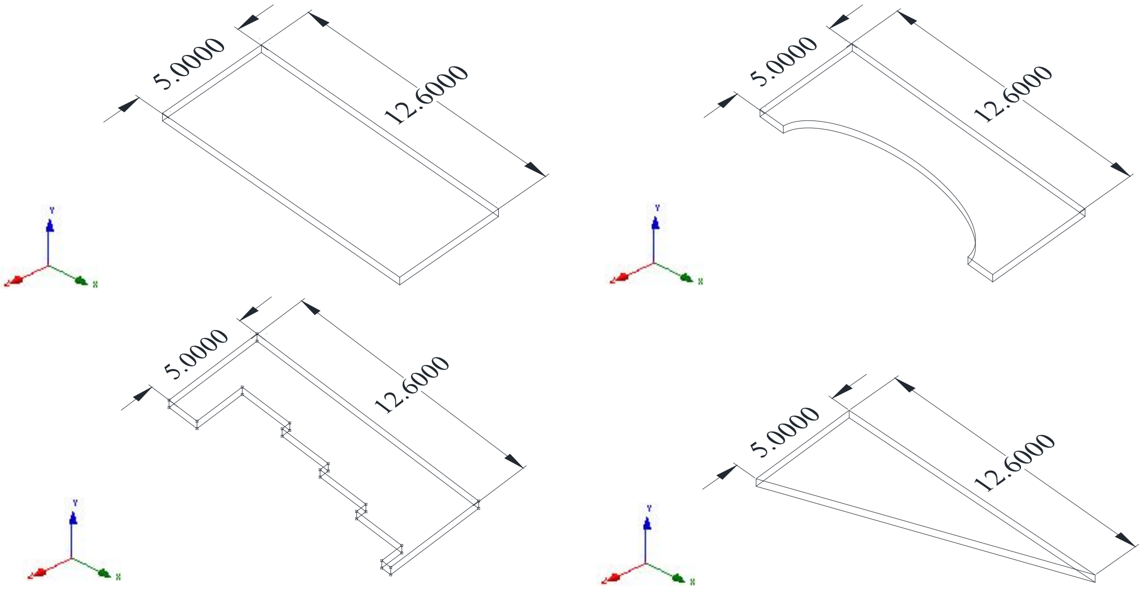


**Fig.6.** Slots of rectangular, elliptical, slope and triangular profiles, with a thickness of 0.28mm

Figures representing the crack simulation results of the four different shapes, show a remarkable change in the impedance variation signals when the crack shape changes

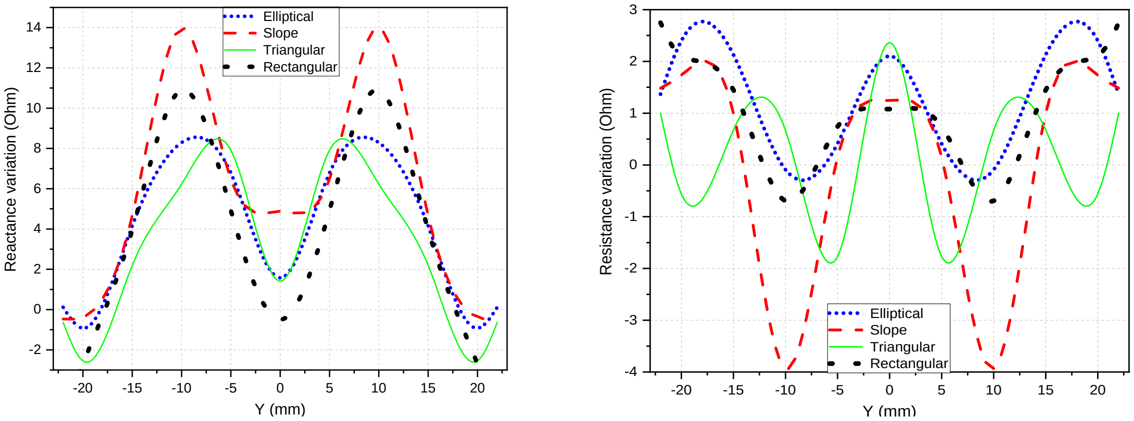


**Fig.7.** Impedance variation of the different flaw shapes

## 4. INVERSION RESULTS

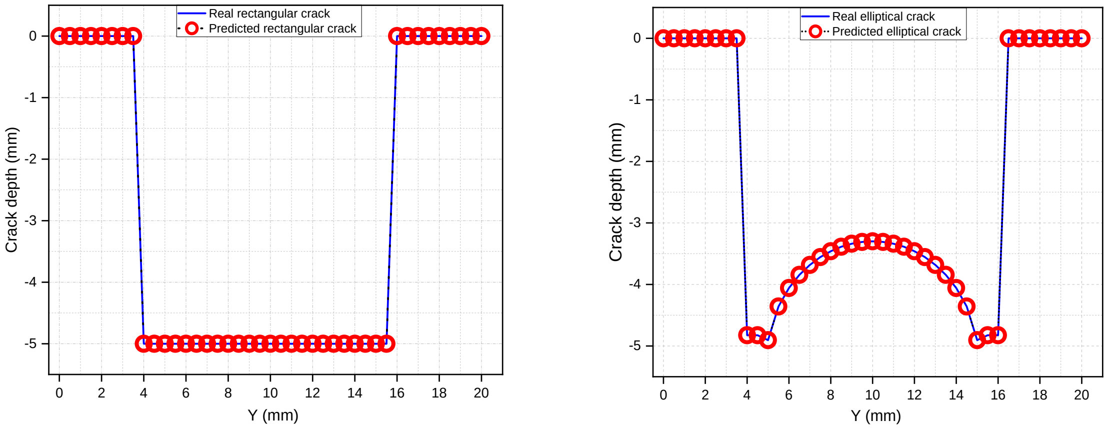
To estimate the defect shapes (Fig. 6), we use an inversion technique. In fact, the problem at hand may be formally represented as the inversion of a model that returns the distribution of the impedance variation over the accessible object’s surface from the geometric characteristics. In order to overcome the problem of analytically studying the electromagnetic interaction between the probe and the specimen, we propose to approximate it through a neural network trained by means of a set of simulated data. The well-known model approximation abilities exhibited by neural networks does in fact provide us with a powerful tool for shaping black-box data-based models of electromagnetic interaction phenomena [10, 11, 12, 13].

Artificial neural networks which are composed of highly interconnected processing elements, called neurons, can be trained to perform arbitrary mappings between sets of input-output pairs [14]. This is achieved by adjustment of the weights of interconnections after training through the presentation of examples [15]. Neural network performance has been proven robust when faced with incomplete, fuzzy or novel data. Previous work has shown that neural networks can also be used as an efficient means of solving electric and/or magnetic inverse problems [16,17].

The neural network structure used is the feed forward multi-layer perceptron (MLP) which is composed of a number of simple processing units, called perceptrons organized in layers.

The training of the MLP is performed using the back-propagation learning algorithm on training sets composed of input-output examples. The input is assumed to be the impedance variation of the probe coil while the output is the crack shape. These impedance variations are computed through a 3D finite element simulation and validated by an experimental companion.

The neural network's approximation ability is a crucial point, in order to assess it, we performed an analysis of the results given by the trained MLP in comparison to the actual model responses. Fig. 8 shows superimposed the actual crack profiles and the results provided by the network.



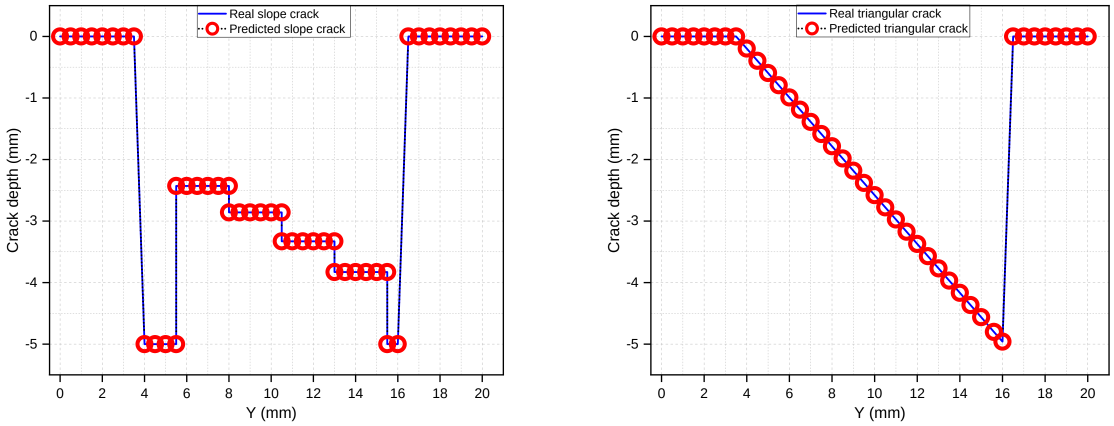


**Fig.8.** Comparison of neural network's and model's outputs for the four defect shapes

## 5. CONCLUSION

The aim of this paper was to present an ECT technique for detecting and estimating the defect size and shape in conductive parts, the technique that we propose allows to overcome one of the main limitations of the inverse algorithm, the required knowledge of the direct model. The accuracy of this model has been highlighted by comparing calculation and experimentation results for different crack sizes and shapes. The obtained data are used to train multi-layer neural network. Simulation results confirm the effectiveness of the proposed approach in estimating the flaw size and shape.

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