# Study on thin open crack detectability of NDT induction thermography technique for magnetic material

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**In this paper, one proposes an original 3D finite elements approach in order to study the capacity of the NDT induction thermography technique to detect thin cracks in nonlinear magnetic pieces. The discretization within the crack is based on degenerated shell elements. Results are compared to the classical volume meshing method.**

***Index Terms*— NDT, induction thermography, nonlinear materials, thin region, shell degenerated elements.**

## I. Introduction

THE nuclear industry is related to many environmental constraints such as high temperature and pressure. This can lead to the appearance of defects that can interfere with the nominal operation of the installations. To prevent this, Non-destructive testing methods (NDT) are used. For surface defects encountered in the nuclear field, the classical methods used are penetrant testing (PT) and Magnetic Particle Inspection (MPI). These methods are very efficient for detecting surface defects but present some drawbacks related to surface treatment and inspections cadence. In order to avoid these problems, new NDT techniques are investigated. The main goal is to find an alternative to these two classical methods.

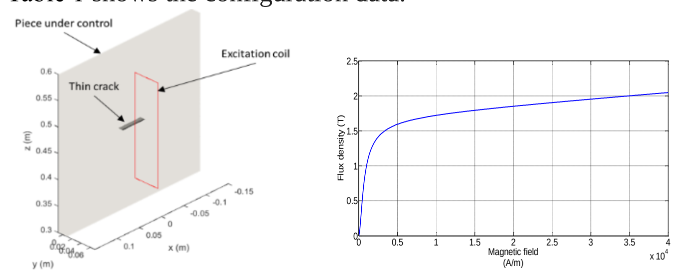
Induction thermography (IT) is one of these new techniques [1]. In this technique, the work piece is heated by means of electromagnetic induction. The presence of surface or sub-surface defects can either deviate the induced current path and generate areas with intensified currents, or create an obstacle to the heat diffusion. In both cases, a thermal imbalance is created and could be recorded by means of a thermal camera. Thermal contrasts are used for results exploitation: signal processing algorithms applied to the temporal evolution of the temperature profile. In addition of using a double detection mechanism, this technique permits to overcome the difficulties of the classical methods by being contact less (which avoids surface treatment problems) and fast (the heating can be accelerated by changing the supply parameters).

A study in depth of this technique requires the use of numerical modeling. In this paper, an original 3D modeling of the technique is proposed for a classical nuclear defect case: a reactor vessel shell with a very thin surface open crack. This test case represents a non-linear electromagnetic problem (magnetic material) with a large scale factor between the vessel shell's dimensions and the crack's dimensions, coupled to a thermal problem. A classical volume mesh in the crack's area will lead to numerical inaccuracies due to the distortion of the mesh in addition to a strong numerical cost. Ren proposes an original type of elements to discretize this kind of thin regions: Whitney's degenerated shell elements [2]. These elements were used for computing the fields in linear, multi-layer and anisotropic materials by [3]. One proposes an extension of the use of these elements to nonlinear materials. Simulation results will be compared to a totally meshed problem. Once the approach is validated, the results of a parametric study will be presented and several contrasts will be tested.

## II. Simulation Case

Fig. 1.a shows the geometry of the problem. The reactor vessel shell is heated by a square-shaped coil fed with a sinusoidal current. The vessel shell's radian is big enough to allow us to consider the heated portion as a parallelepipedic piece. The shell of the vessel is made of a magnetic material whose magnetization curve is shown on Fig. 1.b.

Table 1 shows the configuration data.




*a) Problem solved* *b) Magnetization curve B=f(H)*

Fig. 1. Simulated case

TABLE I
CONFIGURATION DATA

| Data | Value |
|---|---|
| Piece's dimensions (Length x width x thickness) | 30cm x 30cm x 2cm |
| Electrical conductivity | 2e7S/m |
| Crack's dimensions (Length x width x thickness) | 50mm x 0.1mm x 10mm |
| Supply's frequency | 2 kHz |
| Current | 100 A |
| Initial relative permeability | 400 |

## III. **A**-V FORMULATION

The matrix form of the discrete **A**-V formulation for a nonlinear case in a harmonic problem reads:

$$\begin{bmatrix} \mathbf{M_w} & \mathbf{C_{w\varphi}} \\ 0 & \mathbf{M_\varphi} \end{bmatrix}\begin{bmatrix} \mathbf{X}_A \\ \mathbf{X}_v \end{bmatrix} + j\omega \begin{bmatrix} \mathbf{N_w} & 0 \\ \mathbf{C_{w\varphi}}^t & 0 \end{bmatrix}\begin{bmatrix} \mathbf{X}_A \\ \mathbf{X}_v \end{bmatrix} = \begin{bmatrix} \mathbf{F}_{js} \\ 0 \end{bmatrix} \quad (1)$$

The componnents of $\mathbf{M_w}$, $\mathbf{C_{w\varphi}}$, $\mathbf{M_\varphi}$, $\mathbf{N_w}$ and $\mathbf{F}_{js}$ are given as follows :

$$(\mathbf{M_w})_{ij} = \int_{\Omega_c} \frac{1}{\mu(H)} \mathbf{rotw}_i . \mathbf{rotw_j}\, d\Omega \quad (2)$$

$$(\mathbf{C_{w\varphi}})_{ij} = \int_{\Omega_c} \sigma\, \mathbf{grad}\varphi_j . \mathbf{w}_i d\Omega \quad (3)$$

$$(\mathbf{M_\varphi})_{ij} = \int_{\Omega_c} \sigma\, \mathbf{grad}\varphi_i . \mathbf{grad}\varphi_j d\Omega \quad (4)$$

$$(\mathbf{N_w})_{ij} = \int_{\Omega_c} \sigma \mathbf{w}_i . \mathbf{w}_j d\Omega \quad (5)$$

$$(\mathbf{F}_{i^s})_j = \sum_{f=1}^{N_f} i^s{}_f \int_{\Omega-\Omega_c} s_f\, \mathbf{w_j} d\Omega \quad (6)$$

Where nodal shape functions, edge shape functions and facet shape functions are denoted as φ, **w** and s respectively. The parameters μ(H) and σ represents the magnetic permeability and the electrical conductivity respectively. The total domain Ω is divided into a conducting region $\Omega_c$ and a non-conducting region (region with an imposed current included) $\Omega$ - $\Omega_c$.

In order to solve this problem, an iterative Newton Raphson method is used [4]. In each step, the relative permeability is computed based on the magnetization curve of the material (Fig. 1).

## IV. THERMAL PROBLEM

The heat source of the thermal problem is the volume power density calculated from the electromagnetic problem. The matrix form of the discrete thermal formulation in a transient problem is:

$$\left[[M_\theta] + \frac{[N_\theta]}{\Delta t}\right][X_{\theta,i}] = \left[F_p + \frac{[N_\theta]}{\Delta t}[X_{\theta,i-1}]\right] \quad (7)$$

Where $X_{\theta,i}$ represents the temperature rise at the instant i with respect to the initial temperature, the time step Δt is fixed.

The components of $M_\theta$, $N_\theta$ and $F_p$ are given as follows :

$$(\mathbf{M}_\theta)_{ij} = \int_{\Omega_c} \lambda\, \mathbf{grad}\varphi_i . \mathbf{grad}\varphi_j d\Omega \quad (8)$$

$$(\mathbf{N}_\theta)_{ij} = \int_{\Omega_c} \rho C_p \varphi_i . \varphi_j d\Omega \quad (9)$$

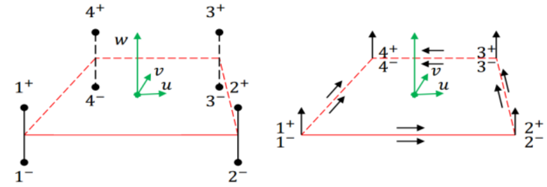
$$(\mathbf{F}_p)_j = \int_{\Omega_c} p_j \varphi_j d\Omega \quad (10)$$

Where λ represents the thermal conductivity, ρ the specific mass, $C_p$ the specific heat and $p_j$ the volumic power density.

## V. SHELL ELEMENTS

In order to discretize the crack one uses degenerated shell elements approach. The procedure is to replace the crack by its mean surface during the meshing phase. We first begin by meshing the mean surface of the crack, the nodes and the edges are then doubled by projecting them on the upper and lower surfaces of the mesh. The width of the crack is taken into account during the establishment of the formulation.

Fig. 2 shows the principle of a degenerated hexahedral shell element.




*a) Double layer nodes* *b) Double layer edges*

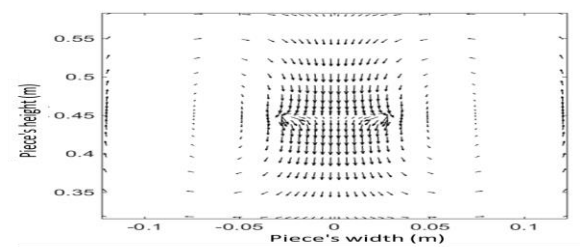
Fig. 2. Principle of degenerated elements

The discretization of scalar and vector potentials by shell elements will be detailed in the full paper.

## VI. SIMULATION RESULTS

Fig 3 shows the eddy current path around the crack. As we intended the current's path is deviated by the presence of the crack.

*a) Real part*




*b) Imaginary part*

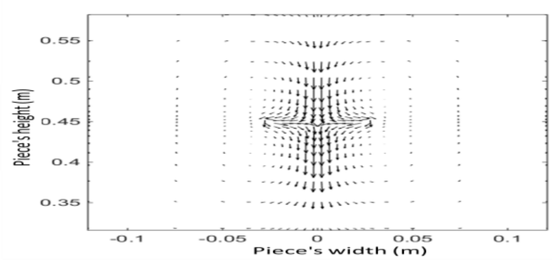



Fig. 3. Eddy current distribution on the piece's surface

## VII. CONCLUSION

In the full paper, comparison between classical volume mesh and degenerated elements mesh will be shown followed by a study on influential parameters where several contrasts will be tested.

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