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A Model-Assisted Probability of Detection Study on Induction Thermography Technique

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In this paper, one proposes a model-assisted probability of detection approach to study the reliability of detecting special defects. The approach is based on a 3-D finite-element T-Ω formulation with circuit coupling. This model is then applied to calculate performances of induction thermography method to detect thin open cracks in vessel reactor shell in nuclear installation.

Index Terms—Induction thermography (IT), non-destructive testing (NDT), probability of detection (PoD).

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 (NDT) methods are used. For surface defects encountered in the nuclear field, the classical methods used are penetrant testing and magnetic particle inspection. These methods are very efficient for detecting surface defects but present some drawbacks related to prior surface preparation and inspection cadence. In order to avoid these problems, induction thermography (IT) NDT technique presents interesting advantages [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 detected by means of a thermal camera. Thermal contrasts are used for results exploitation [2]. In addition of using a double detection mechanism, this technique permits to overcome the difficulties of the classical methods by being contact less, fast, and global. One of the most important aspects of an NDT technique is the reliability. The probability of detection (PoD) is a meaningful approach to evaluate it [3]. The main goal is to obtain an output curve describing the probability of detecting a flaw in terms of a characteristic quantity (depth of a crack and radius of a porosity). This leads to determine the limit characteristic quantity that allows the detection of the flaw. Traditionally, PoD data are collected from the experimental campaigns [3]. This can be costly and time-consuming. To this respect, the use of simulation is seen as a great prospect to make PoD evaluation more affordable. This concept is known

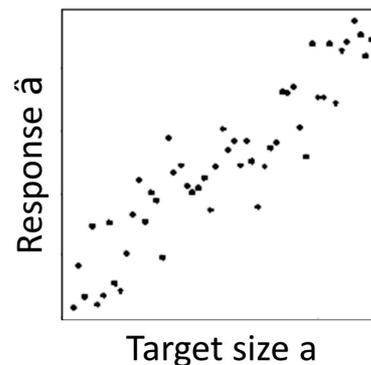


Fig. 1. Example of uncertainties due to the variability of influential parameters.

as model-assisted PoD (MAPOD). MAPOD approach has been elaborated for several NDT classical techniques [4]. With regard to IT, the studies done are mostly experimental [5]. To meet the expectations of MAPOD, the numerical model used must be very accurate and fast. In the literature, only a few publications on modeling of IT is found [6], [7] only with simplified models which are not suitable for an MAPOD. In this paper, a global MAPOD approach applied to IT with highly accurate 3-D multi-physic model coupled with circuit equations is presented. The global tool is then applied to study a classical nuclear defect case: a reactor vessel shell with a very thin surface open crack.

II. PRINCIPLE OF POD

A. Purpose

Repeated inspections of a specific flaw can lead to different responses. This is due to the natural variability parameters (environmental parameters and physical parameters). An illustration of this phenomenon is presented in Fig. 1 where the output signal variation in terms of crack size is plotted. As one can see, for the same crack size, the output signal is different from a test to another.

In order to take into account this variability, a probabilistic approach has to be proposed. The main goal of a PoD is to evaluate the detection performance of an NDT process,

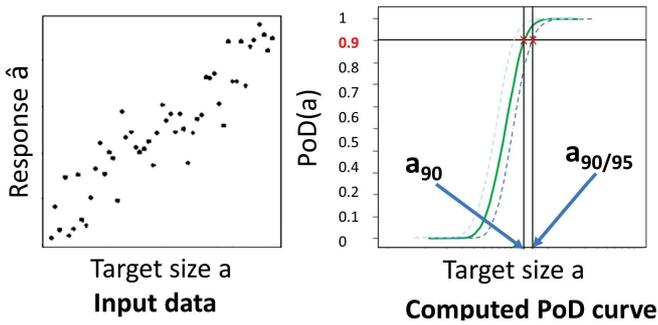


Fig. 2. PoD methodology.

while taking into account the variability of influence parameters [3]. By using this approach, one aims to answer to the following question: what is, according to its size, the probability of detecting a defect, while using a specific NDT process?

B. Tools

The exploitation is done by using “PoD curves” giving the PoD value in terms of the defect size. Using these curves, one can quantify the size of the smallest crack that can be detected using a specific technique. Indicators are used to this end [3].

- 1) a_{90} : Corresponds to the size of the smallest defect that provides a PoD greater than 90%.
- 2) $a_{90/95}$: Corresponds to the size of the smallest defect for which we have a probability greater than 95% to have a PoD of 90%. It is more used than a_{90} since it takes into account the uncertainties encountered in the computation process of the PoD.

In order to have a clearer vision of these indicators, Fig. 2 presents a simplified scheme of a PoD procedure. Where the green curve represents the computed PoD curve. Its 95% lower confidence bound is represented by the dark blue dotted curve. One can see that practically, a_{90} is obtained from the computed PoD curve, while $a_{90/95}$ is obtained from its 95% lower confidence bound.

C. Main Goal

Determination of PoD curves via a purely experimental approach requires a large number of experiments performed on representative test blocks containing representative defects. This can be costly and time-consuming, and sometimes not feasible. For instance, a minimum amount of 40 different defects location shall exist when an “a versus \hat{a} ” analysis is performed, while this minimum is 60 for a Hit–Miss analysis [3]. In order to avoid this, an MAPOD approach can be elaborated. While using an MAPOD approach, input data generated by the experimental campaigns are replaced by results computed by NDT simulation software [4]. Nowadays, NDT simulation software is completely deterministic: for a fixed configuration, a unique set of results is obtained. Uncertainties have to be introduced in the simulation process [4]. To achieve that, the key idea (MAPOD) is to introduce variations in the input parameters of the model which lead to the uncertainty on the output of the simulation.

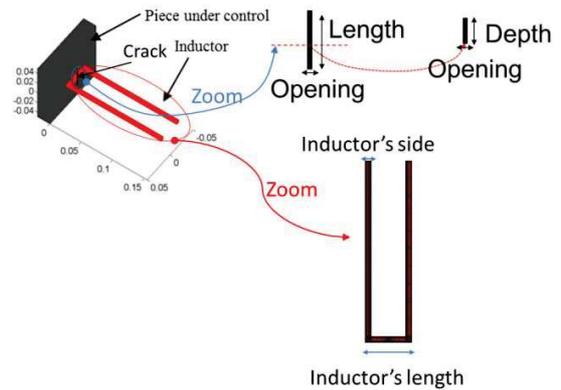


Fig. 3. Final configuration.

D. Methodology

The integration of uncertainties is done following these steps:

- 1) identifying influent parameters whose variability will be taken into account;
- 2) characterizing the statistical distribution of each influent parameter;
- 3) computing PoD curves from the set of simulated cases.

III. APPLICATION CASE

A. Global Presentation

The aim of this paper is to evaluate the detection performance of IT in the severe context of defects encountered in the nuclear industry. One of the most common and difficult defect cases concerns surface inspections of thin open cracks in reactor vessel shells. This case will be investigated in this paper. The proposed methodology is divided into three steps: implementation of the numerical model, definition of a nominal configuration, and application of the MAPOD procedure.

B. Procedure

1) Implementation of Numerical Model:

a) *Presentation of the problem:* Fig. 3 presents the geometry of the problem. The U-shape of the coil was previously selected to maximize thermal response of the piece to be investigated. It has been placed perpendicularly to the crack orientation.

b) *3-D multi-physic numerical model coupled with circuit equations:* The implemented numerical code has to fulfil the following criteria: fast computational time. In this purpose, a T– Ω formulation is used. Accurate results: it has been shown that some physical phenomenon has to be taken into account, while doing an inductive thermography inspection. The most influential phenomenon is the current repartition within the inductor [8] so circuit coupling have to be taken into account. Fig. 4 presents the study domain where D represents the whole domain. The conducting part of D is noted D_c and the non-conducting part D_c^c . Γ_{ae} represents the inductor’s electrode from which the current I_a is imposed. Since the inductor is a massive one, the current computation is done in it. Consequently, the inductor, with the piece under control,

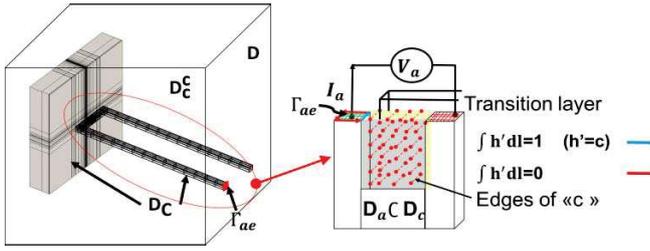


Fig. 4. Numerical study domain.

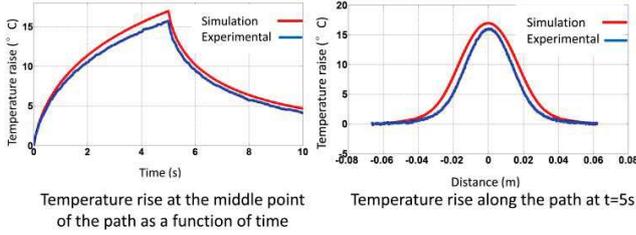


Fig. 5. Experimental validation of the model.

is a part of dc [9]. T- Ω formulation allows fast computation but engages some numerical complexities with multi-connected regions [9]. The introduction of a cut C makes the studied domain simply connected. A basis function c is associated with the cut with circulation equal to 1 in the so-called “transition layer.” This function allows us to associate global quantities to the T- Ω formulation as it can be seen in the following equation:

$$\int \frac{1}{\sigma} \text{rot}(h) \cdot \text{rot}(h') + \int \mu \frac{\partial h}{\partial t} h' = V_a \oint h' dl$$

$$h = \sum_{a \in \text{edges}} T_a A_a + \sum_{n \in \text{nodes}} \Omega_n N_n + c I \quad (1)$$

where V_a is the voltage of the inductor D_a . In that case the function base c is the sum of edge basis function associated with the edges in red (Fig. 4). Γ_{ae} is one of the two electrodes of D_a (assuming that in the opposite electrode the potential value is zero). Once the electromagnetic volumic power density is calculated, the temperature is then computed by a classical weak coupling approach with thermal equations.

c) *Comparison with the experimental results:* In order to validate the model, an experimental validation has been done on a flat piece of a real reactor vessel shell heated by U-shaped massif inductor. Temperature raise profiles have been compared after 5 s of heating as shown in Fig. 5.

As one can see, the developed model shows a very good accuracy with experiments with less than 5% error and acceptable calculation time. The numerical model takes into account voltage supply, natural and radiative convection, and current distribution in the coil. The numerical model implemented can now be used in a global MAPOD procedure.

2) *Definition of Nominal Configuration:* The nominal configuration represents the ideal case where defects can easily be detected. It is obtained by a classical parametric study.

TABLE I
NOMINAL CONFIGURATION

Parameters categories	Parameters	Values
Crack parameters	Length	10 mm
	Depth	1 mm
	Opening	10 μm
Vessel parameters	Electrical conductivity	$2.32 \times 10^5 (\Omega \cdot \text{m})^{-1}$
	Relative permeability	50
	Thermal conductivity	$52 \text{ W} \cdot \text{K}^{-1} \cdot \text{m}^{-1}$

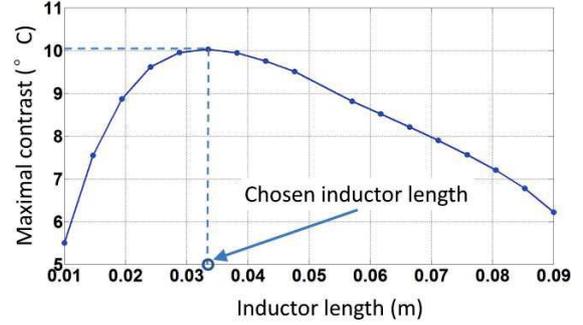


Fig. 6. Maximal contrast variation in terms of inductor length.

TABLE II
NOMINAL VALUES OF THE OPERATORY PARAMETERS

Parameters categories	Parameters	Values
Supply	Voltage amplitude	150 V
	Voltage frequency	180 kHz
Inductor dimensions	Inductor length	3.35 cm
	Inductor side	5 mm
Inductor position	Lift off	3.2 mm

The crack to be detected is a thin open crack widely found, while inspecting reactor vessel shells. Table I presents the parameters value of the crack and physical parameters of the reactor vessel.

For this parametric study, the suitable criteria is the absolute contrast which is the difference of temperature with or without defect [2]. The criteria of acceptance are defined according to the following:

- 1) higher absolute contrast in order to maximize the detection;
- 2) temperature raise lower than 200 °C.

An example of this study is presented in Fig. 6 where the maximal absolute contrast has been drawn for each value of the inductor length.

Following the same procedure for all the parameters, the nominal configuration is then obtained. Table II shows the values fixed for each parameter.

With this nominal configuration, the MAPOD procedure can be done. For this paper, the parameter investigated is the defect depth. The goal is to quantify, following the MAPOD approach, the smallest crack depth with IT configuration taking into account the variability of all influent parameters. The chosen range of crack depth value is [0.1 mm 20 mm].

3) Application of the MAPOD Result:

a) *Identification of influent parameters:* While doing a PoD approach experimentally, many parameters could fluctuate from an inspection to another. The goal here is to select

TABLE III
INFLUENT PARAMETER WITH RELATED DISTRIBUTIONS

Class	Parameters	Nominal value	Distribution	Interval
Operator	Voltage	150V	Uniform	Deviation +/- 10%
	Frequency	180kHz	Uniform	Deviation +/- 10%
	Lift off	3.2 mm	Uniform	Deviation +/- 10%
Defect	Length	10 mm	Normal	Stand dev = 2 mm
	opening	10 μ m	Normal	Stand dev = 2 μ m

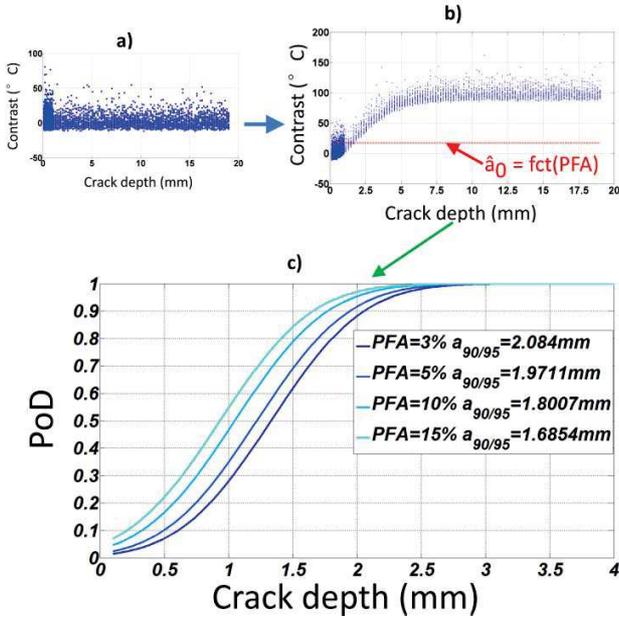


Fig. 7. (a) PoD results for crack depth is the noise that allows to compute \hat{a}_0 . (b) Input data for PoD. (c) PoD curves for different PFA values.

from all the parameters the ones whose fluctuation has a big impact on the absolute contrast value. In order to do this, simulations had been done where each parameter was slightly shifted from its nominal value. For this paper, only parameters that could fluctuate in a real experimental case are evaluated. Table III shows investigated parameters. Once identified, a statistical distribution should be associated with each selected parameter. Formal studies has been used to associate each parameter to a distribution [4].

Now that all the needed data are known, one can proceed to the computation of PoD curves.

b) Computing PoD curves from the set of simulated cases: The PoD curve will be computed for the crack depth. Since the output data of the inductive thermography process is a signal amplitude (absolute contrast). The chosen PoD analysis for those type of data is the “a versus \hat{a} ” approach [3]. In our case, “a” refers to the crack depth and “ \hat{a} ” to the absolute contrast. For this approach, the PoD corresponds to the probability to have an output signal \hat{a} better than an already fixed threshold \hat{a}_0 [3]

$$\text{PoD}(a)=\text{Prob}(\hat{a}>\hat{a}_0). \quad (2)$$

Which can be read as the probability that the measured magnitude exceeds the detection threshold knowing that the defect has a size “a.” For more technical details of a versus \hat{a} approach, refer to [3]. The choice of \hat{a}_0 is done by introducing the concept of the probability of false alarm (PFA). Practically speaking, simulating non-defect cases by taking into account the variability of influent parameters allows us to compute the noise parameters. Then, an explicit relation between these parameters, PFA and \hat{a}_0 allows the determination of \hat{a} [3]. Fig. 7 gives an illustration of how this threshold \hat{a}_0 is computed. It presents also the PoD results of the crack depth for different values of PFA. As one can see, the value of the smallest depth detected decreases when the PFA value increases. Indeed, by fixing an important value of PFA one reduces the detection threshold which allows us to have more chances to detect smaller defect. But, by doing this, one have more possibilities to have a detected signal generated by noises than by the presence of a real defect. A PFA = 5% seems to be a good balance between performance of detection and reliability of detection.

IV. CONCLUSION

In this paper, a fast, accurate, and dedicate tool for MAPOD investigations applied to IT is proposed. The method is applied for classical defect case of the nuclear industry and can be easily adapted to other defect cases. This global approach facilitates the quality of investigation and optimization of NDT applied to IT.

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