Inspection of the delamination of magnetic and non-magnetic conducting layers using NDT

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***Abstract*—The partial delamination of two metallic parts, one ferromagnetic and one non-magnetic, is inspected using nondestructive magnetic measurements. Defects of this type occur among others in the reactor of nuclear power plants, and are usually hidden. Low frequency AC current is injected into the metals during the inspection, and the perturbation of the surrounding magnetic field is measured. The authors developed a finite element model for the simulation of the defect-probe interaction, which is necessary for the proper reconstruction of the parameters of the hidden defect. The most important point in this model is the representation of the delamination. Since the volumetric modeling of this defect is found to be ambiguous, a sophisticated surface model has to be derived.**

***Index Terms*—Nondestructive testing; Eddy-current testing; Thin crack model; Ferromagnetic material**

I. Introduction

The aging of nuclear power plants is a common problem nowadays. The extension of their lifetime is of high economic interest. The key point in the prolonged use of the reactors is the regular inspection of their active parts using various nondestructive methods. Even it is worth to develop specific testing methods for each type of defects (corrosion, cracks, deposits, decohesion, deformations, etc). The development should concern the measurement principle, the reconstruction method, probe design, numerical simulations, and benchmarking [1].

In this paper we study the computational aspects of the electromagnetic nondestructive testing (NDT) of a particular defect, which has not been dealt with yet. This defect is an inter-layer decohesion arising between a ferromagnetic and a non-magnetic metal part, and is usually hidden by further metallic regions. This delamination can be very dangerous, causing the deformation of the layers and thus inhibiting normal operation of the reactor.

II. Defect configuration and measurement setup

The simplified configuration of the measurement is shown in Fig. 1. The parameters of the non-magnetic material (stainless steel) are $\mu_n \approx \mu_0$ and $\sigma_n = 1.3 \times 10^6$ S/m. Those of the ferromagnetic material (carbon steel) are $\mu_f = 1000\mu_0$ and $\sigma_f = 5.6 \times 10^6$ S/m. The thickness of the non-magnetic front plate is 6.5 mm.

The exciting current is injected via two electrodes through the front plate at the same distance above and below the magnetic/non-magnetic interface. AC current is used in order to avoid the saturation of the magnetic sensor and to eliminate the effect of any DC background field. On the other hand the frequency is kept very low (at about 10 Hz) for receiving the highest possible defect signal. Otherwise the current would flow mainly in the front plate and keep off the region to be examined. The magnetic sensor lies in the plane of the material interface and measures the *x*-component of the field, which seems to be the most practical choice. The sensor's lift-off is 1 mm.

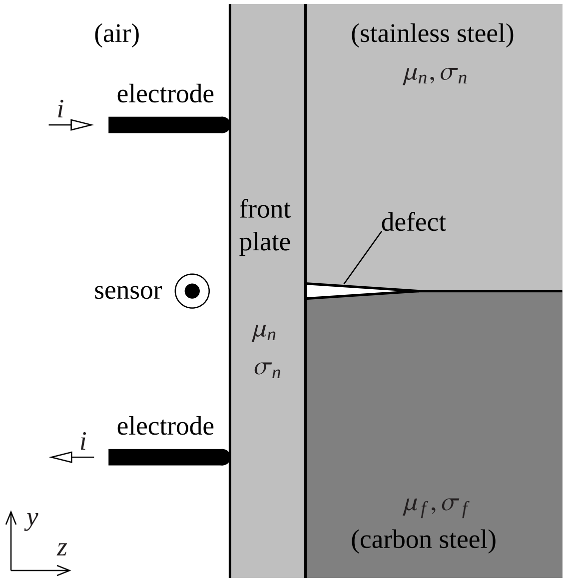

Figure 1: Scheme of the studied measurement setup.

III. Numerical simulation of defect-probe interaction

In a first approach, we modeled the delamination as a thin rectangular crack-like volumetric flaw of zero conductivity and of permeability μ_0. Its dimensions are 20 mm × 10 mm × 1 mm.

The probe signal – i.e. the measurable field distortion due to the presence of the defect – can be computed very efficiently and with high accuracy using a two-step decomposition method [2]. In the first step the so-called *unperturbed* field is computed in the absence of the defect. Then the *perturbation* of the field can be directly obtained from a model containing the defect, where the unperturbed field appears as an impressed electric or magnetic current. The time harmonic equations

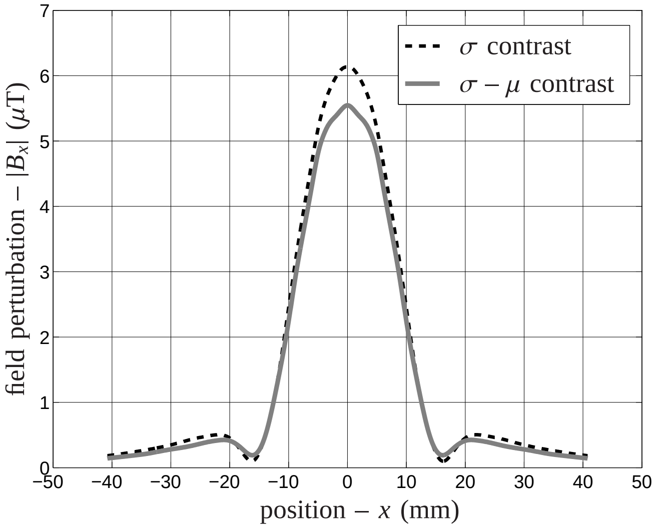

Figure 2: Computed probe signals.

written for the field perturbations as unknowns are

$$\nabla \times \mathbf{H} = \sigma \mathbf{E} + \mathbf{J}^i \tag{1}$$

$$\nabla \times \mathbf{E} = -j\omega\mu \mathbf{H} - \mathbf{K}^i \tag{2}$$

in which the source electric and magnetic currents can be expressed as

$$\mathbf{J}^i = (\sigma - \sigma^u)\mathbf{E}^u \tag{3}$$

$$\mathbf{K}^i = j\omega(\mu - \mu^u)\mathbf{H}^u \tag{4}$$

respectively. Superscript u stands for "unperturbed", referring to the fields and material parameters of the configuration without defect.

The question arises naturally. In which material should we place the flaw: the ferromagnetic, the non-magnetic, or both? We carried out two simulations and got quite different results. In the first case the flaw resided right above the material interface (in the stainless steel), while in the second case right below it (in the carbon steel). The probe signal of the former exceeds the latter by about 16% at the maximum (see Fig. 2).

One may argue that the reason of this deviation should be the change in the relative position of the flaw to the excitation and to the probe. But this is not the case. We have also measured these effects separately, and they can alter the signal by no more than 4% (together). Actually, the main reason is that in the second case there is a permeability contrast (4) in addition to the conductivity contrast (3), but the two effects counteract, as is easy to see from (1)–(2), and this causes a decrease in the signal.

In principle the difference should vanish if we chose thinner and thinner flaws. This just means one has to use an appropriate surface model for a delamination type defect in FEM, which is justified by the ambiguity of the volumetric model.

Defects with negligible thickness are traditionally modeled as double sided surfaces, representing the jump of a scalar potential on them [2], [3]. This type of surface model is described in [4], [5] with some recent improvements in [6]. However, this model needs revision in several aspects in order to be applicable for the problem at hand. Differences that should be considered are the following:

- The crack is on the interface separating two materials of very different magnetic permeability.
- The crack is fully embedded in the metal (there is no such a thing that "crack mouth").
- The so-called *thin skin limit*, which is utilized in some of the cited works, is no longer valid at such low frequencies.

IV. SUMMARY

Surface crack models will be revisited, and an appropriately modified one will be presented in the full version of the paper. Results obtained with the surface model will be compared to those of the volumetric model as well as to measured data.

The introduced problem can also be considered as a benchmark initiative of wide interest, for example the developed technique can be useful for testing the delamination of the conductive coating from a ferromagnetic substrate.

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