AN EDDY CURRENT MODEL BASED ON PARAMETRIC DESCRIPTION OF INDUCED CURRENT LOOPS

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INTRODUCTION

Our objective is to design a "forward model" for steam generator tube flaw characterization, using eddy current technique. An investigation of the existing forward models was made.

Dodd and Deeds [1] computed the impedance of a coil situated above two sound infinite plane conductors. Flaw-present models can be classified into five approaches : in the first approach, the flaw is seen as an electrical or magnetic source (Burrows [2], Burke and Rose [3]); using certain assumptions, Maxwell equations are solved analytically (Nair and Rose [4], Auld et al. [5], Lewis [6]); they are solved using numerical techniques (Bowler et al. [7]); they are solved using the perturbation method (Burke [8], Antimorov et al. [9]); in the last approach, the electrical and magnetic phenomena are described using parametric functions (Groshong et al. [10]).

The study of the existing forward models shows that most analytical models are two-dimensional, are designed for an uniform exciting field, assume that the skin depth is much smaller or much larger than the flaw depth and above all are only applicable to flaws with specific geometry. Models based on numerical techniques are the only ones to be three-dimensional and general. However, in the case of cracks, they require a very thin mesh and a too prohibitive computing time. The parametric approach, which is more

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straightforward, hence more general and faster, appears to be the most appropriate for designing a forward model to characterize steam generator tube flaws.

In this paper, we propose a three-dimensional forward model based on a parametric approach. This model estimates the impedance change caused by a flaw located in a non-magnetic conductor with linear, homogeneous and isotropic conductivity. A quasi-static regime is assumed.

FORWARD MODEL DESIGNING

We chose to parameterize the induced currents. These eddy currents allow us to determine the coil impedance change using the Lenz law. The continuous distribution of the induced currents is approximated using a discrete set of current loops, each of them being run by a current of intensity i_q.

Impedance Change Calculation

If the shape of the current loops is known, the resistance R_q, the self inductance L_q of each current loop Cq and the mutual inductance M_{qp} between the current loops Cq and Cp can be computed. The intensity of the current loop Cq is expressed as a function of other current loop intensities and of the coil intensity i_C :

$$i_q = \frac{-j\omega M_{qC} i_C - j\omega \sum\limits_{p=1 \text{ and } p\neq q}^{N} M_{qp} i_p}{R_q + jL_q\omega}, \quad \forall q \in [1,N] \qquad (1)$$

where M_{qC} is the mutual inductance between the current loop Cq and the coil, ω is the driving current pulsation and N is the number of current loops.

The resolution of the linear system (1) yields the intensity of each current loop. The flux ϕ of the flux density **B**, produced by the induced currents through the coil, is given by :

$$\phi = \sum_{q=1}^{N} M_{qC} . i_q . \qquad (2)$$

Knowing ϕ, the impedance change is calculated by the Lenz law.

Model Validation

Using the proposed model, we calculated the impedance change due to a sound plane conductor. The coil is normal to the conductor. Therefore, the configuration is axisymmetric, the eddy current distribution can be approximated by circular current loops. We compared the results to those obtained by the Dodd and Deeds model [1] and by a finite element code. Comparisons are given in table I.

The plane conductor is 1.55mm thick, has a conductivity of 1MS/m and a relative permeability of 1. The coil has an inner radius of 1mm and an outer radius of 1.75mm, is 2mm high and has 328 turns. It is normal to the plane conductor and the lift-off is 0.1mm. The driving current frequencies are those used in French eddy current testing of Pressurized Water Reactor 900MW steam generator tubes. The continuous current distribution is approximated by 75×20 current loops, 75 in the radial direction and 20 in the depth one.

Table I. Impedance changes due to an infinite plane conductor.

Frequency (kHz)	100	240	500
Dodd and Deeds' model : ΔZ_D (Ω)	5.65 - 4.21i	16.89 - 19.99i	36.90 - 60.88i
Finite element : ΔZ_F (Ω)	5.65 - 4.15i	16.89 - 19.95i	36.89 - 60.79i
Proposed model : ΔZ_M (Ω)	5.72 - 4.16i	16.87 - 19.93i	36.79 - 60.66i
Relative difference R_D (%)	1.28	0.26	0.34
Relative difference R_F (%)	0.99	0.11	0.23

The relative differences R_D and R_F are defined as :

$$R_D = \frac{|\Delta Z_M - \Delta Z_D|}{|\Delta Z_D|} \text{ and } R_F = \frac{|\Delta Z_M - \Delta Z_F|}{|\Delta Z_F|} \tag{3}$$

The comparisons show a good agreement between impedance changes calculated by Dodd and Deeds [1], by the finite element code and by the proposed model.

We also calculated the impedance change due to three holes (see fig.1), which are coaxial with the coil. In these cases, the configurations are also axisymmetric. The results were compared to those obtained by the same finite element code. The first hole has a diameter of 3mm, is 50% deep and is on the same side of the plate as the coil. The second one also has a diameter of 3mm, is 50% deep and is on the side opposite to the coil. The third one has a diameter of 1mm and is a through-wall hole. The plane conductor and the coil are the ones described before. Comparisons are given in tables II, III and IV.

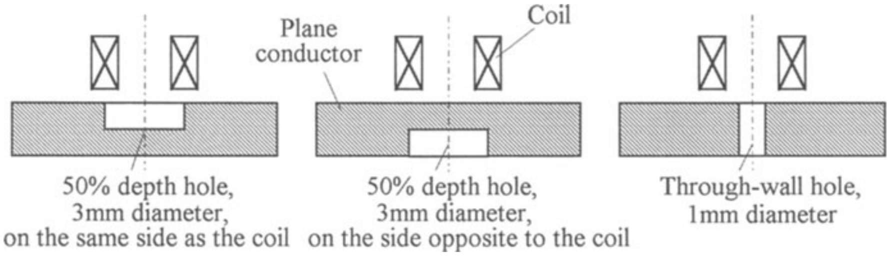

Figure 1. Holes considered for the comparisons between the proposed model and the finite element code.

Table II. Impedance changes due to a hole of 50% depth, of 3mm diameter, on the same side as the coil.

Frequency (kHz)	100	240	500
Finite element : ΔZ_F (Ω)	-1.002 + 0.480i	-3.572 + 3.057i	-8.366 + 11.033i
Proposed model : ΔZ_M (Ω)	-0.999 + 0.481i	-3.569 + 3.053i	-8.366 + 11.028i
Relative difference (%)	0.31	0.09	0.04

Table III. Impedance changes due to a hole of 50% depth, of 3mm diameter, on the side opposite to the coil.

Frequency (kHz)	100	240	500
Finite element : ΔZ_F (Ω)	-0.088 + 0.158i	0.187 + 0.540i	0.970 + 0.239i
Proposed model : ΔZ_M (Ω)	-0.087 + 0.159i	0.188 + 0.538i	0.971 + 0.238i
Relative difference (%)	0.77	0.26	0.11

Table IV. Impedance changes due to a through-wall hole of 1mm diameter,

Frequency (kHz)	100	240	500
Finite element : ΔZ_F (Ω)	-0.0186 + 0.0129i	-0.0454 + 0.0735i	-0.0406 + 0.2073i
Proposed model : ΔZ_M (Ω)	-0.0185 + 0.0128i	-0.0454 + 0.0731i	-0.0411 + 0.2069i
Relative difference (%)	0.94	0.46	0.32

The comparisons also show a good agreement between the impedance changes, due to a hole, calculated by the finite element code and those calculated by the proposed model.

Actually, the proposed model can be applied to any axisymmetric configuration. In such a configuration, the current loops are circular. In three-dimensional configurations, the current loops are no longer circular. For example, in the case of a plane conductor with a slot, the current loops are deformed by the flaw. A parametric description of this deformation must then be found.

Impedance Change Due To A Slot

In a first step, we are only interested in the cases of through-wall slots normal to the plane conductor. Also, we restricted our study to impedance changes along the slot axis.

In order to get a parametric description of the current loop deformation, we analyzed the results obtained with a three-dimensional finite element code which provides a realistic distribution of the induced currents in the slot neighborhood. We derived the following law : the current loops are bent in such a way that the resistance is minimized while the flux of **B** through the coil is maximized. Also we considered that there is no crossing between the current loops. Using these two laws, a parametric description of the current loop deformation was produced.

In our parametric description, we considered that the current loops which intersect the slot are the only ones to be deformed, the others remain circular (see fig.2). The deformed current loops are bent as described in figure 3. Three parameters c1, c2 and c3, which characterize the concentration of the current loops around the slot, are used to describe their deformation: c1 determines how close to the slot surface the current loops go, c2 determines how close to the slot tip the current loops go and c3 determines how deep the current loops go. The distances d1, d2 and d3, given in figure 3, are calculated as a function of c1, c2, c3, the altitude z0 of the current loop and the distance d between the tip of the slot and the intersection point of the non deformed current loop and the slot: $d1 = |z0| / c1$, $d2 = |z0| / c2$ and d3=d/c3. The bigger the parameters are, the more concentrated the current loops are.

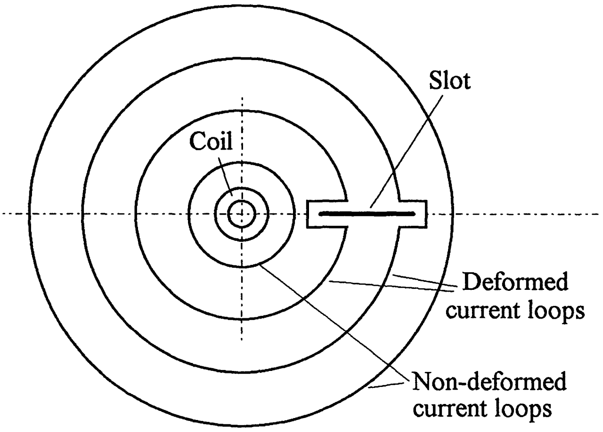

Figure 2. Deformed and non-deformed current loops.

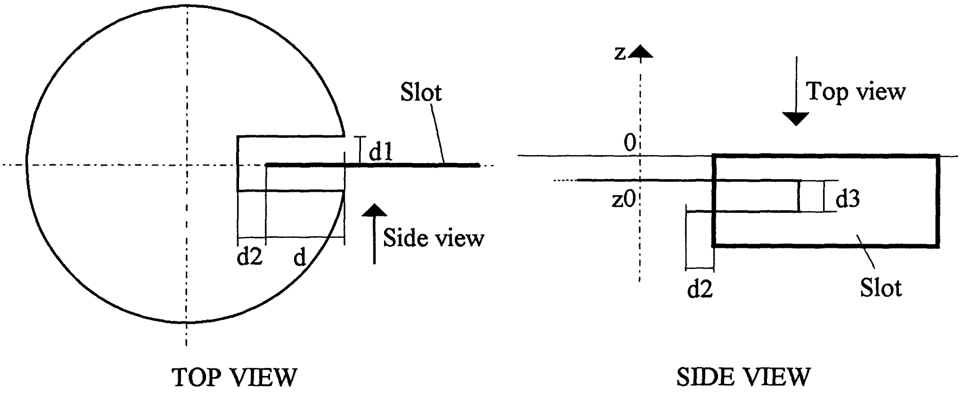

Figure 3. Current loop bending.

By optimizing the parameters c1, c2 and c3 with respect to the impedance changes due to a 10 mm length slot, measured experimentally, we obtained the results shown on figure 4. The slot is 0.1mm wide. The plane conductor and the coil are those described before. The driving current frequency is 240kHz. The origin of the x-axis in figure 4 is the 10mm slot center.

The previous parameter values were used to compute the impedance change due to a 20mm slot. This slot is also 0.1mm wide. Results are given in figure 5. The origin of the x-axis in figure 5 is the 10mm slot center.

Results (figure 5) show a fairly good agreement between the impedance change phases calculated by the proposed model and the one measured experimentally, but a poorer one for the impedance change amplitudes. In order to get a better agreement, some investigations are currently made to improve the parametric description of the current loop deformation.

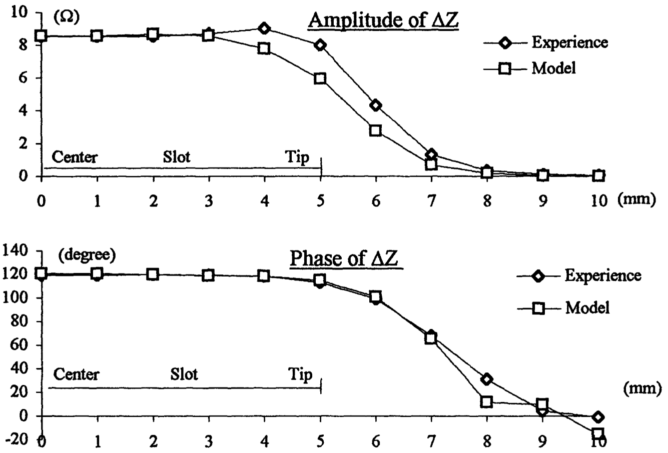

Figure 4. Impedance changes due to a through-wall slot of 10mm length.

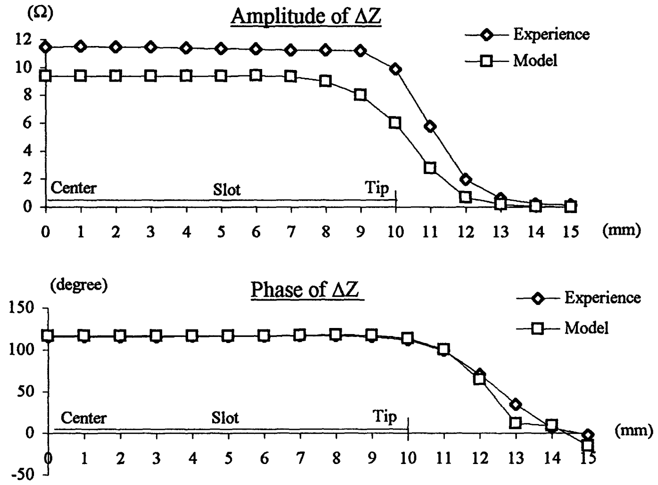

Figure 5. Impedance changes due to a through-wall slot of 20mm length.

CONCLUSION

In the framework of the steam generator tube flaw characterization, we proposed a forward model based on the parametric approach. The continuous eddy current distribution is approximated using a discrete set of current loops. In the case of axisymmetric configurations, the comparisons show that the results obtained with the proposed model agree with those produced by a finite element code whether there is a flaw or not, and also with those computed using Dodd and Deeds model when there is no flaw. In the case of three-dimensional configurations, a parametric description of the deformation of the current loops is necessary since the latter may not be circular. The difficulty in designing the model lies in the search for a relevant parametric description. Nevertheless, some preliminary results show that this parametric approach is promising.

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