Modelling the ECT of U-Bend Steam Generator Tubes by the Boundary Element Method

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Abstract. We are interested in modelling the eddy current testing of U-bend tubes in steam generators that are part of the second barrier containment of radioactive materials in nuclear pressurized water reactors. The bending may cause a variation in thickness and an ovalization of the tube, and sometimes produces a dent at the intrados of the U-bend. It also affects the movement of the probe that can be tilted and shifted. The detection and characterization of defects in this zone requires a signal analysis due to geometric distortions and thus their modelling. Numerical simulation of these phenomena is challenging as the method used must be sufficiently flexible to adjust to small geometric distortions and accurate enough for the digital noise does not disturb their low signal variations. As part of collaboration between CEA LIST and IRSN, that is the French public expert in nuclear and radiological risks, we used an integral formulation resolved by the boundary element method to simulate the effects of bending for eddy current testing. For this a specific adaptation of the integral model developed at CEA LIST has been introduced. We will present the model, this adaptation and the main results obtained of which some will be compared to experimental measurements carried out as part of this study.

Introduction

Steam generator tubes are part of the second barrier containment of radioactive materials in pressurized water reactors, thus the detection of flaws in these tubes is an important stake. The integrity of these tubes is evaluated by periodic checks based on the technique of eddy current testing (ECT), and the modelling of the ECT is a powerful tool to interpret the measured signals. In particular, the detection and characterization of defects in the bending of SG tubes requires a signal analysis due to geometric distortions and thus their modelling. The bending may cause a variation in thickness, an ovalization [1] [2] [3], and may also affect the trajectory of the probe which can be tilted and shifted. Numerical simulation of these phenomena is challenging as the method used must be sufficiently flexible to adjust to small geometric distortions and accurate enough for the digital noise does not disturb their low signal variations. As part of collaboration between CEA LIST and IRSN, that is the French public expert in nuclear and radiological risks, we used an integral formulation resolved by the boundary element method to simulate the effects of bending for eddy current testing. For this a specific adaptation of the integral model developed at CEA LIST has been introduced. We will present the model, this adaptation and the main results obtained of which some will be compared to experimental measurements carried out as part of this study.
This specific adaptation of the model requires knowledge of the relevant parameters on the variation of the signal in order to properly model taking into account realistic computational capabilities. For this reason a study of influence of different geometric parameters that describe the shape of the bending and the localization of the probe has been performed. Then first comparisons of the simulated signals to experimental measurements, which were carried out as part of this study, were made.

The main outlines of the integral approach and the boundary element method are discussed in section 2. The EC probe, the geometric description of the bending and the pre-computation process are given in section 3. Part of the axial probe sensitivity study and first comparisons with experimental measurements are presented in sections 4 and 5, respectively.

2. Surface Integral Equation

Under linear regime in an isotropic piecewise homogeneous medium, the 3D problem can be expressed as an equivalent transmission problem at the interface between homogeneous parts of the medium by a suitable integral representation form [4]. The goal then becomes to compute the electric \( J = n \times H \) and magnetic \( M = E \times n \) surface current densities (here \( n \) stands for the normal at the interface, \( E \) and \( H \) are the electric and magnetic fields). A Galerkin discretization of the variational form then enables us to approximate the physical solution by solving a linear system.

Compared to the finite element method (see [5] for the modelling of the ECT signal in a U-bend tube), the number of unknowns of the linear system is dramatically reduced (but the matrix is full with complex filling) and therefore the use of a direct solver becomes possible. A direct solver is far more effective than an iterative one when we face a system that is ill-conditioned or presenting many RHS (right hand sides), provided that the number of unknowns remains limited (a few tens of thousands). Hence it is generally well suited to ECT applications for which we can count thousands of RHS (positions of the coil) in a restricted computational domain, due to the localized support of the source and to negligible propagation effects. A higher-order approximation (i.e. increasing the polynomial degree of the expansion) further reduces the number of unknowns for a given precision, therefore making more accessible the direct solver. In practical terms, the increase of the order of the mesh allows the use of surface elements with curved edges that are particularly effective for modelling accurately the slight geometric variations we have encountered in this study.

Such a high order boundary element method is currently implemented at CEA LIST. Firstly developed for magnetostatic applications such as the modelling of 3D ferrite cores [5] (available in the 2016 release of the CIVA software [7]), this approach has since been expanded to the quasi-static regime and to low frequency electromagnetic applications in general [8]. In particular, we now have a formulation that is robust enough to consider geometric variations and the introduction of simple defects such as notches. The research and development of tools dedicated to a fine and fast modelling of more complex defects is ongoing and will continue to grow in the coming years.

3. Settings

3.1 Configuration

Part of the study focuses on the modelling of the signal for a SAX-like axial probe in steam generators tubes for 1300 MW nuclear power plants. The nominal outer diameter of the tube is 19.05 mm, its thickness is 1.09 mm and its conductivity is rounded to 1 MS m\(^{-1}\). The SAX-like probe is made of two identical cylindrical coils (Figure 1) and can be operated either in
absolute or differential mode. Here a small outer diameter (14 to 15 mm) is required to pass the bending. The position of the probe is specified relatively to the axis of the tube, with a shift and a tilt that are negative/positive at the intrados/extrados (Figure 1).

![Diagram showing settings for the SAX-like probe.](image)

**Fig. 1.** Settings for the SAX-like probe.

The bending may cause an increase/decrease of the nominal thickness at the intrados/extrados, a decrease along the intrados-extrados axis and an increase in the cross direction, and even a slight torsion of the section of the tube. These variations are not abrupt but smooth, and reach a maximum at the top of the bending.

3.2 Pre-Computation

The quality of the discrete mesh is crucial as low changes of the curvature may lead to high numerical noise with regards to the slight variations of signal we are looking for. As a first step, meshing is performed on a portion of the straight tube for nominal parameters. This mesh is composed of quadrilateral elements with curved edges, whose size increases as the element is closer from the truncation. Then, for a given axial location of the probe in the bending, corresponding distortions are applied to the straight mesh to obtain the deformed one. Finally the probe is shifted and tilted as wanted. Representations of the straight mesh and of some deformed meshes are given in Figure 2.

All tilt and shift variations are handled in a single calculation for a given axial location of the probe. Since the mesh follows the axial location of the probe, numerical noise is negligible from one position to the other. The numerical parameters (truncation of the tube, number and order of the elements…) were set in order to get a relative deviation of 0.1% with the analytical results obtained with CIVA [7] in the straight tube. In particular, the higher-order expansion of surface current densities is a powerful way to achieve such an accuracy, as shown in Figure 3.
4. Parametric Study

We seek to identify the most influential input parameters on the variation of impedance. To this end, we vary the parameters one after the others and perform simulations for a sufficient number of positions of the probe so as to constitute a database. These results are then interpolated to obtain the impedance all over the interval of variation of input parameters.

Only the absolute mode was considered for symmetrical deformations of the tube with a non-tilted probe as the differential signal is identically zero. In other cases the two modes were simulated with a shift that varied from a centred position to a position close to the extrados (lift-off of 0.1 mm). The results that are reported here correspond to the absolute mode with only one emitting-receiving coil with an outer diameter of 14 mm at 120 kHz.

4.1 Curvature

Here the radius of the bending varies without deforming the section of the tube (nominal diameter and thickness are considered). The inverse of the radius of the bending is taken from
0 (straight tube) to $\frac{1}{2}$ inch$^{-1}$ (Figure 4). The corresponding simulated impedances are presented in Figure 6 and suggest that the variation of the radius of the bending does not dramatically impact the signal.

![Fig. 4. Simulated variations of the radius of the bending.](image)

### 4.2 Ovalization

A 2.25 inch bent tube with varying section is now considered. The nominal thickness is preserved and we impose an ovalization from 0 to 15% of the nominal diameter that preserves the internal perimeter of the tube (Figure 5). Since the distance between the intrados and the extrados decreases as the ovalization increases, the shift interval reduces and no shifting is tolerated anymore at maximal ovalization (the lift off is 0.1 mm). The corresponding simulated impedances are presented in Figure 7. Ovalization has a significant impact on the signal, which is of the same order of that of the shift.

![Fig. 5. Simulated ovalizations of the tube.](image)
Fig. 6. Impedance’s variation with respect to the radius of the bending and the shift.

Fig. 7. Impedance’s variation with respect to ovalization and shift.
4.3 Other parametric variations

The influence of variation of the thickness (negligible with the axial probe and for variations that can be associated to the bending process) and of the tilt of the probe (that has a major influence in differential mode) have also been investigated. Furthermore, the signal obtained with respect to a given trajectory of the probe at the connection between straight and curved portions of the tube have been simulated.

5. First comparisons with experimental data

First comparisons concerned a SAX with a 15 mm outer diameter, operated in absolute mode with one emitting-receiving coil for various frequencies (120, 280 and 600 kHz), for two distinct SG tubes with a 3 inches bending. Notice that our experimental measurements were made for a slow motion of the probe that is maybe not representative of the practical testing configuration. X-rays of the motionless probe in the tube (Fig. 8) indicate that we have an important shift should and a negligible tilt at the top of the bending (but not at the connection between straight and curved portions).

Signals were calibrated with respect to an outer groove (30% width, 1 mm long) that is present in the straight portion of the second tube: the standard signal we took is 350 mV and -90° at 120 kHz, 1 V and 0° at 280 and 600 kHz. We report in Table 1 the minimal and maximal variations in amplitude and phase measured in the two bent tubes and the simulated signal obtained with a shifted probe of 0.5 mm then of 0.72 mm. There is a good agreement for the phase, but the simulated signal amplitude is largely underestimated for these calculations.

Table. 1. Measured variation of impedance (↕) in the bending for the two tubes versus simulated impedance for a 0.5 mm then a 0.72 mm shift with the surface integral equation (SIE) method.

<table>
<thead>
<tr>
<th></th>
<th>120 kHz</th>
<th>280 kHz</th>
<th>600 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXPE TUBE 1</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>0.79 V, 173.6°</td>
<td>4.0 V, -74.3°</td>
<td>9.6 V, -34°</td>
<td></td>
</tr>
<tr>
<td>0.92 V, 175°</td>
<td>4.9 V, -72.4°</td>
<td>12 V, -32.7°</td>
<td></td>
</tr>
<tr>
<td>EXPE TUBE 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.66 V, 166°</td>
<td>3.8 V, -74°</td>
<td>9.2 V, -33.6°</td>
<td></td>
</tr>
<tr>
<td>0.75 V, 167°</td>
<td>4.4 V, -73°</td>
<td>10.6 V, -32.8°</td>
<td></td>
</tr>
<tr>
<td>MODEL SIE 0.50</td>
<td>0.25 V, 173.5°</td>
<td>1.5 V, -69.3°</td>
<td></td>
</tr>
<tr>
<td>SIE 0.72</td>
<td>0.53 V, 172.8°</td>
<td>3.2 V, -69.3°</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 8. X-ray of the (motionless) probe in the tube.
6. Conclusion and Perspectives

A specific adaptation of the surface integral equation solved by the boundary element method has been introduce to simulate the EC testing of U-bend SG tubes. This adaptation lies on the distortion of a reference mesh and on the use of high-order elements to fit geometric variations and to improve the approximation of the unknown current densities. A preliminary study of the influence of the various input parameters has been performed and first comparisons with experimental measurements have been shown.

These comparisons with experimental data are in progress. The goal is to achieve a good agreement for the phase on various configurations such as for a rotating coil (for which the same kind of computation has also been introduced), then to explain the underestimation of the amplitude in terms of the input parameters (ovalization…). Finally, we will be able to go further on the study of the trajectory of the coil at the connection between the straight and bent parts, and we could investigate the influence of the bending on some defect’s signal.

References