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# Modelling the Influence of the Tube Support Plate on the Eddy Current Testing of the Steam Generator: Sensitivity Study & Validation

Audrey VIGNERON<sup>1</sup>, Edouard DEMALDENT<sup>2\*</sup>,  
Jean-Marc DECITRE<sup>3</sup> and Thierry SOLLIER<sup>4</sup>

<sup>1</sup> Université Paris-Saclay, CEA, List, F-91120, Palaiseau, France; E-mail: [audrey.vignerone@cea.fr](mailto:audrey.vignerone@cea.fr)

<sup>2</sup> Université Paris-Saclay, CEA, List, F-91120, Palaiseau, France; E-mail: [edouard.demaldent@cea.fr](mailto:edouard.demaldent@cea.fr)

<sup>3</sup> IRSN, France; E-mail: [jean-marc.decitre@irsn.fr](mailto:jean-marc.decitre@irsn.fr)

<sup>4</sup> IRSN, France; E-mail: [thierry.sollier@irsn.fr](mailto:thierry.sollier@irsn.fr)

\*Contact: [edouard.demaldent@cea.fr](mailto:edouard.demaldent@cea.fr)

## Abstract

Eddy current testing (ECT) of Steam Generator (SG) tubes is part of the maintenance program of Nuclear Power Plants. Tube Support Plates (TSP) are usually only considered as extraneous signals for tube inspection. However, for long-term operation of SGs, there is a safety concern related to the build-up of deposits in the TSPs flow holes. The clogging-up of the TSPs flow holes affect the safe thermal-hydraulic operation of SGs. The deposits come from the feedwater train and are mostly iron oxides (magnetite) with a weak electrical conductivity and magnetite permeability. The ability of ECT probes to detect and characterize TSPs deposits is therefore of great interest. The most common and industrial ECT technique, the bobbin coil, averages the surrounding electromagnetic field over 360°, whereas the geometry of tri-foiled and quadri-foiled TSPs, and thus of clogging, is rather complex and non-axisymmetric, hence motivating the evaluation of the performance of conventional ECT rotating probes used for SGs tubes inspection. Although simulation is a powerful tool to support such a study, it requires dedicated models to be made available to NDT experts, and CEA develops ECT physical models in CIVA for this purpose. In addition to standard fast CIVA modules based on 3D semi-analytical or 2D numerical calculations restricted to canonical or axisymmetric parts, respectively, CEA develops a module dedicated to the simulation of SG tube inspection based on a 3D numerical simulation. This module allows tube deformation such as ovalization, bending or tube expansion. It also allows the addition of external objects such as anti-vibration bars, different geometries of tube support plates and now their clogging by deposits. This model is used to study various influent parameters and to perform benchmarks in the framework of a scientific collaboration between the CEA and the IRSN. Here, the specificity of the TSPs and their clogging justifies qualifying the simulation model before evaluating the influence of material and geometry properties of the deposit as well as the performance of the inspection techniques. We present the main features of the simulation module in CIVA, its experimental validation, and the main trends in the distortion of the simulated signal as a function of variation in the clogging description.

**Keywords:** Eddy current testing, modelling, steam generator tubes, nuclear, clogging, tube support plate

## 1. Introduction

Due to their key role in ensuring nuclear safety in French PWR (Pressurised Water Reactor) nuclear power plants, the steam generator (SG) tubes undergo periodic non-destructive examinations by eddy current testing (ECT) to detect any indications or defects. If the indications identified during an inspection are characterized as flaws having critical dimensions with respect to structural integrity analysis, the affected tube is plugged to maintain the integrity of the barrier between the primary and secondary circuits. If the tubes plugging ratio is too high for a safe operation, steam generators can be replaced. The ongoing research conducted by CEA and IRSN aims to enhance the detection and characterization of defects in SG tubes through ECT.



In this context, simulation tools are being used to assess the effectiveness of existing and upcoming ECT techniques. Tube support plates (TSP) are designed to hold the tubes along their height and to maintain a sufficient distance between the tubes in order to avoid tube-to-tube fretting. TSP provide also support for different mechanical loading during normal and accidental conditions such as seismic loading. TSPs are broached to allow fluids to flow outside the tubes. The foliage (or flow hole) may be subject to a build-up of corrosion products or residues of elements present in the feedwater train. This clogging phenomenon reduces the flow section of water inside the SGs with a detrimental effect on the safe operation of this equipment [1]-[5]. A chemical cleaning of SGs might be required to restore sufficient safety margins for operation.

Simulation tools dedicated to the ECT of SG tubes are available in the CIVA software platform. Based on the mathematical modelling detailed in [6][7], these numerical tools enable sensitivity studies to be carried out on complex inspection configurations such as friction wears under anti vibration bars [8]. Their extension to the inspection of TSPs and clogging was introduced in [9]. Here, we present the (ongoing) experimental validation of these modeling tools for TSPs and their clogging. The experimental set-up is presented in section 2, comparisons on reference flaws in section 3, then in presence of various tube support plates (cylindrical or quadrifoil, magnetic or not, with or without ferrite inserts in the foliage of the non-magnetic quadrifoil plate) in section 4, while concluding comments are provided in section 5.

## 2. Experimental setup

Experimental measurements were made with a bobbin coil probe mounted on a translation bench, see Figure 1. Two tube samples were used, a first tube with the reference defects described in Table 1, and a second tube without defects, enabling the spacer plates to be positioned.



**Figure 1: Experimental bench for axial probes**

**Table 1: Reference flaws**

Label	Dimensions
4Ø1	4 through wall $\Phi 1$ holes, spaced by $90^\circ$
LEG30	Large External circumferential Groove 30% width 20 mm
EG40	External circumferential Groove 40% width 1 mm
IG10	Internal circumferential Groove 10 % width 1 mm

For plate samples were used:

- cylindrical plate in 316L stainless steel
- cylindrical plate in P265GH steel
- quadrifoil plate in 316 L stainless steel
- quadrifoil plate in P265GH steel

and ferrite inserts to simulate clogging, see Figure 2. Figure 3 presents the positioning of the ferrite inserts in the foliage of the quadrifoil plates.



**Figure 2: Cylindrical and quadrifoil plates**



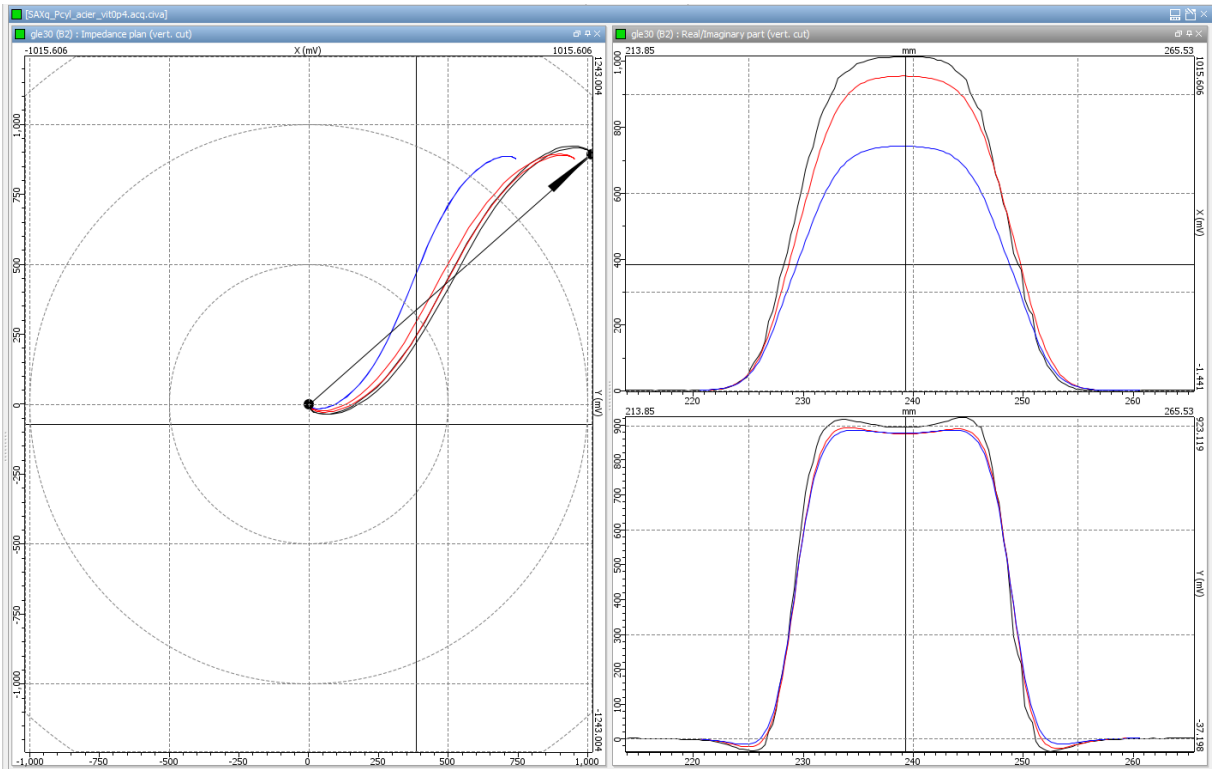
**Figure 3: Positioning the ferrite inserts in the foliage of the quadrifoil plates**

### **3. Validation on reference flaws**

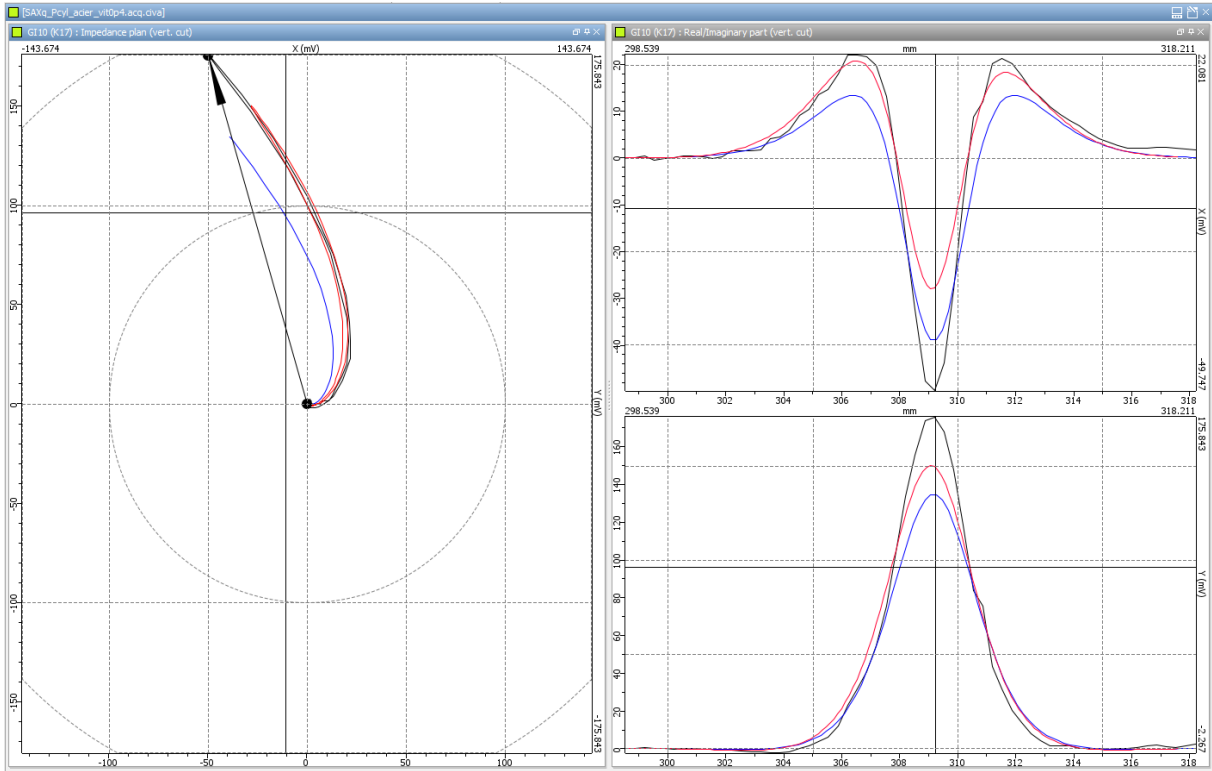
All the experimental acquisitions presented in this section are performed using a 15.4 mm radius bobbin coil probe. The probe is used in absolute mode, and signals are acquired using an impedance meter. The acquired and simulated signals are balanced and calibrated.

Figure 4 to Figure 7 show the experimentally recorded and simulated signals at 120 kHz for the reference defects. The results are presented in Lissajous form (left) and in real and imaginary parts according to the displacement (right). The industrial axial probes for controlling french SG tubes have a core with a magnetic permeability and electrical conductivity different from

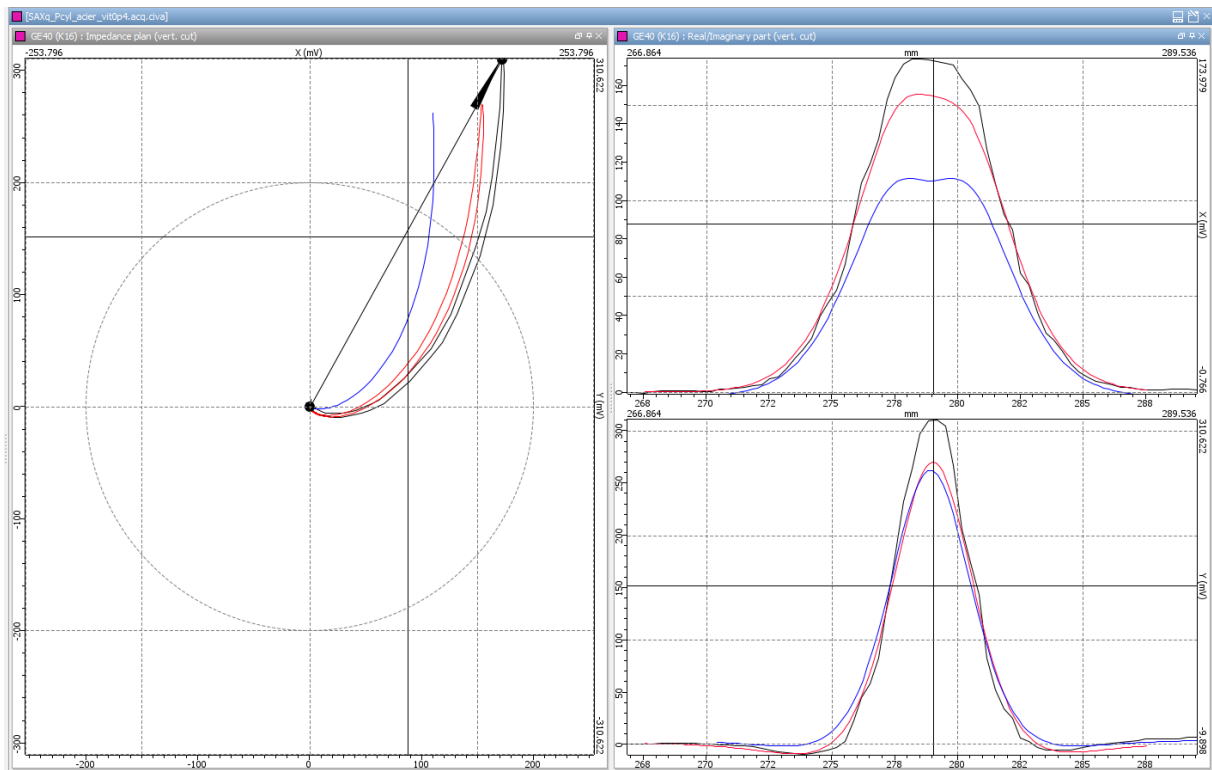
those of air. Simulations on reference defects are therefore carried out with and without the core, the electromagnetic properties of the latter being arbitrarily fixed, see Figure 8.



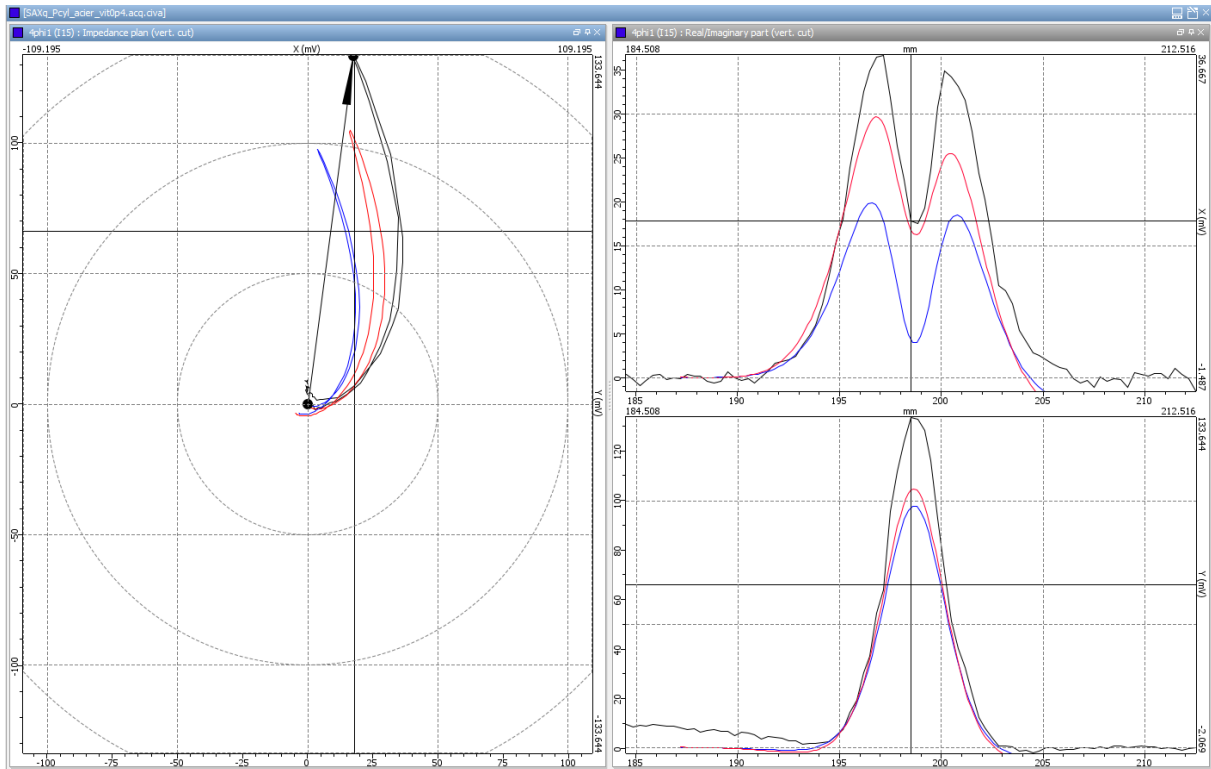
**Figure 4: Experimental (black) and simulated LEG30 fault signal for a bobbin coil probe with (red) and without (blue) core excited at 120 kHz.**



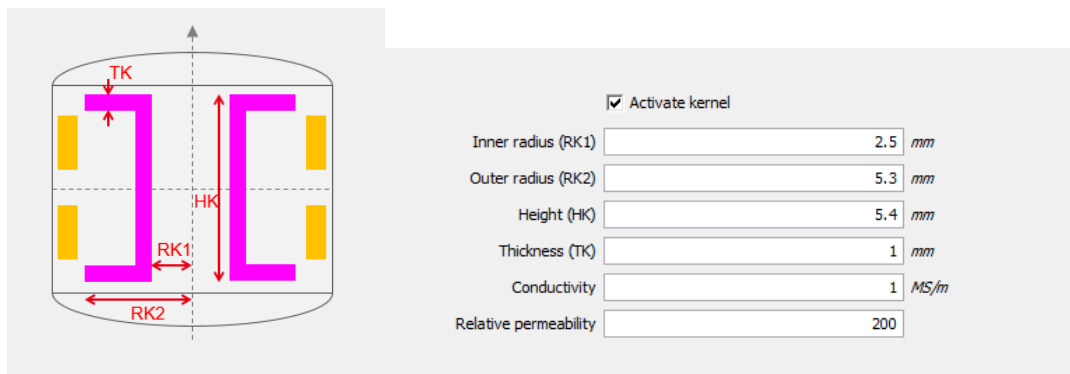
**Figure 5: Experimental (black) and simulated IG10 fault signal for a bobbin coil probe with (red) and without (blue) core excited at 120 kHz.**



**Figure 6: Experimental (black) and simulated EG40 fault signal for a bobbin coil probe with (red) and without (blue) core excited at 120 kHz.**



**Figure 7: Experimental (black) and simulated  $4\Phi 1$  fault signal for a bobbin coil probe with (red) and without (blue) core excited at 120 kHz.**



**Figure 8: Dimensions and electromagnetic properties of the bobbin coil probe core.**

Table 2 show the amplitude and phase of simulated standard defects for the bobbin coil with and without core and signals experimentally acquired. Good agreement is observed between simulations and experimental acquisitions, with the exception of IG10, where the presence of the core reduces the difference in amplitude and phase.

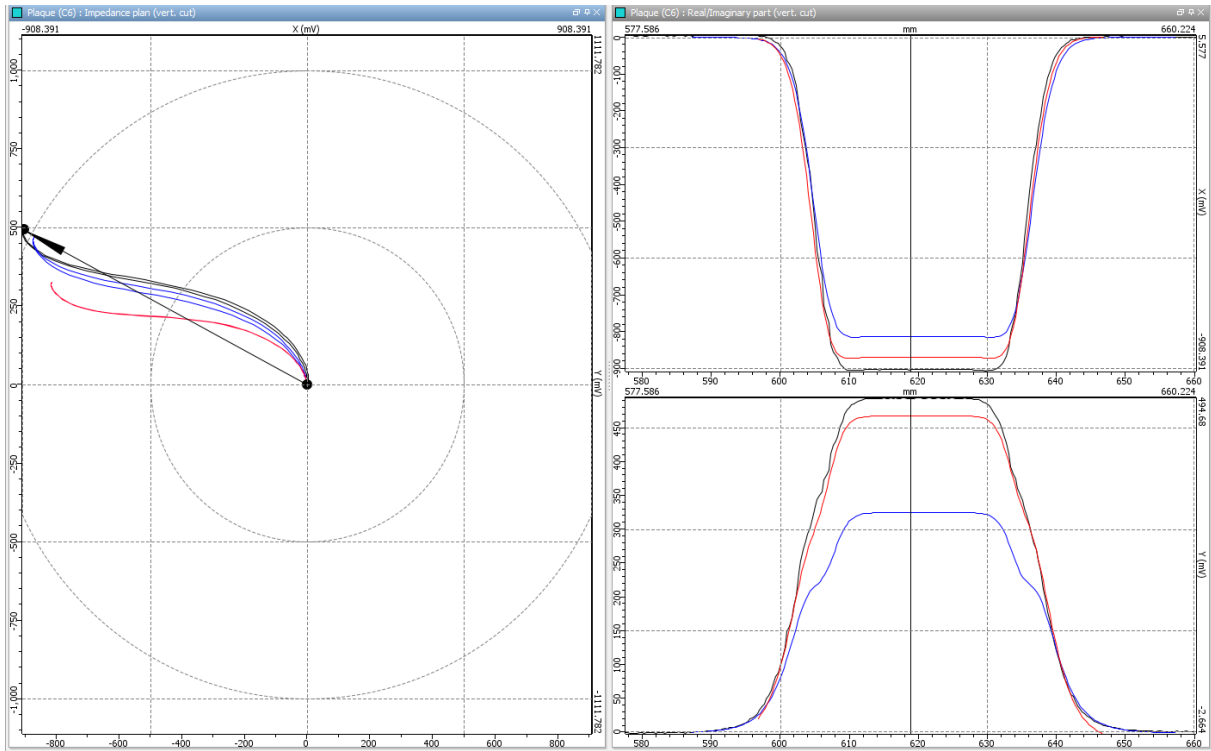
**Table 2: Amplitude and phase deviations of acquired and simulated signals for reference faults at 120 kHz**

	LEG30	IG10	EG40	$4\Phi 1$
Amplitude difference without core [%]	15.1	23.5	20.0	27.4
Amplitude difference with core [%]	4.3	17.0	12.4	21.5

Phase difference without core [°]	8.1	0.4	6.2	5.2
Phase difference with core [°]	1	5.2	0.8	1.3

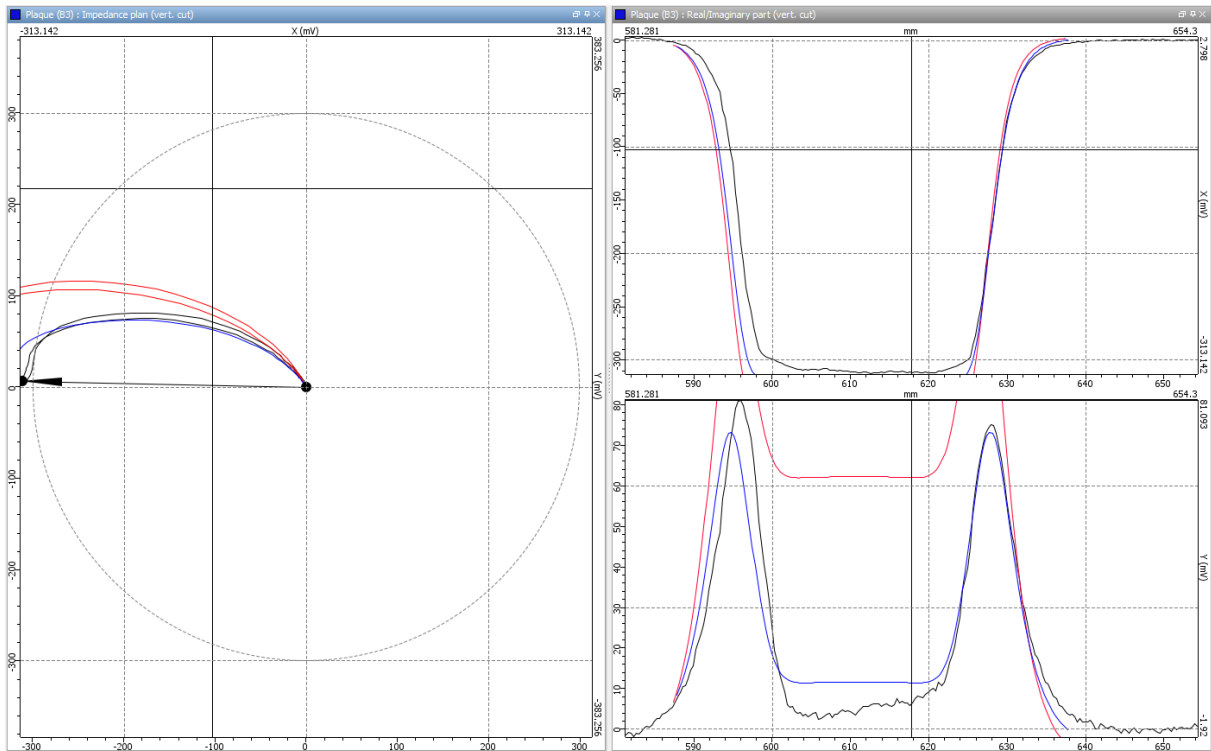
#### 4. Validation on tube support plate

Figure 9 and Figure 10 show comparisons between experimental data and simulations for a cylindrical 316L and P265GH TSPs at 120 kHz. Figure 11 and Figure 12 show the same comparisons for quadrifoil TSPs. Table 3 shows the amplitude and phase difference shown in the figures. It can be seen that there is good agreement between the simulations and the experimental recordings for the cylindrical and quadrifoil stainless steel plates, particularly when the core is taken into account in the bobbin coil. On the other hand, there is a large discrepancy for the steel plates, especially for the quadrifoil plate, and the discrepancy does not decrease in the presence of the core, but even increases. Since the material properties of the steel TSPs are not experimentally characterized yet, we assume that the simulated electromagnetic parameters are not optimal at this stage.

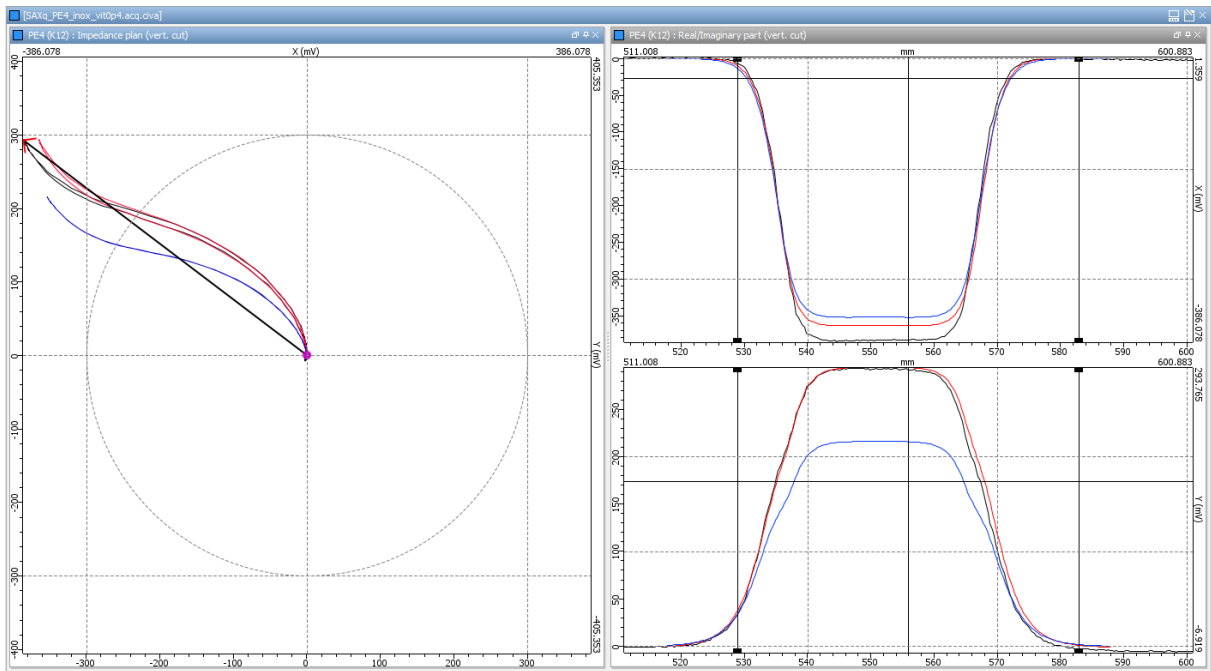


**Figure 9: Signal from the stainless steel cylindrical plate, experimental (black) and simulated for a bobbin coil probe with (red) and without (blue) core excited at 120 kHz.**

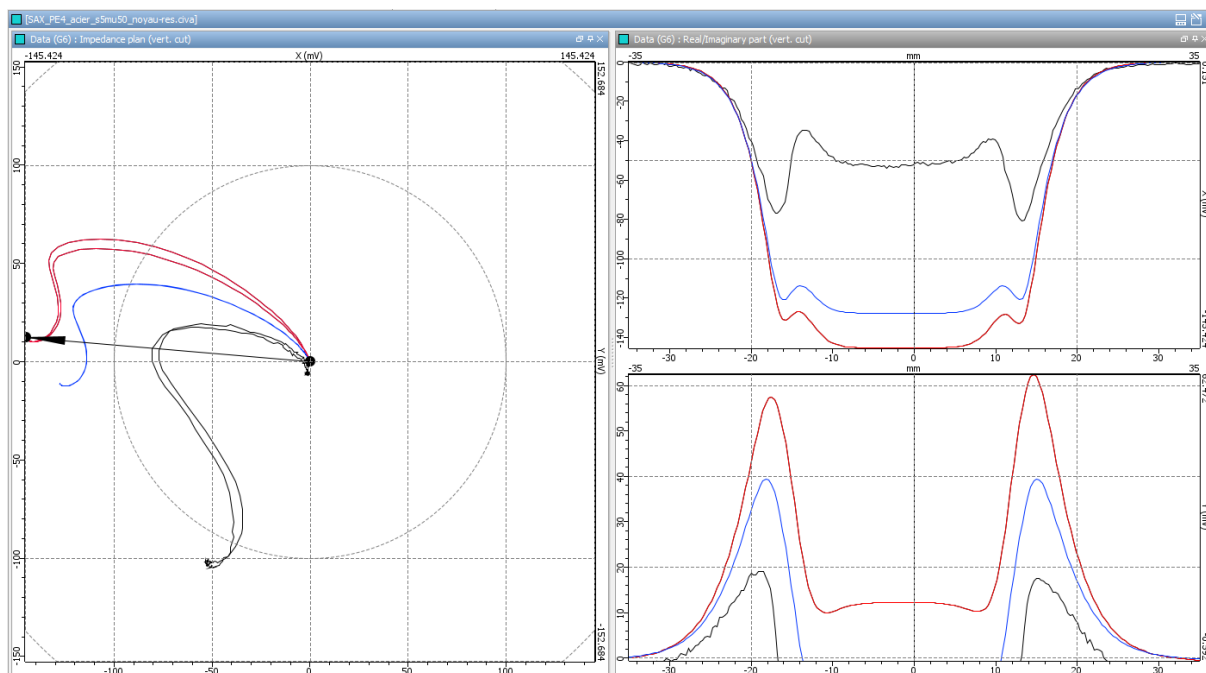




**Figure 10: Signal from the steel cylindrical plate, experimental (black) and simulated for a bobbin coil probe with (red) and without (blue) core excited at 120 kHz.**



**Figure 11: Signal from the stainless steel quadrifoil plate, experimental (black) and simulated for a bobbin coil probe with (red) and without (blue) core excited at 120 kHz.**



**Figure 12: Signal from the steel quadrifoil plate, experimental (black) and simulated for a bobbin coil probe with (red) and without (blue) core excited at 120 kHz.**

**Table 3: Amplitude and phase deviations of acquired and simulated signals for cylindrical and quadrifoil plates at 120 kHz.**

	Cylindrical TSP 316L	Cylindrical TSP P265GH	Quadrifoil TSP 316L	Quadrifoil TSP P265GH
Amplitude difference without core [%]	14.9	4.1	14.6	9.4
Amplitude difference with core [%]	4.1	17.6	3.5	24.8
Phase difference without core [°]	7	1	5.8	59
Phase difference with core [°]	0.6	9	1.7	68.8

We now compare the experimentally acquired and simulated signals for a quadrifoil stainless steel plate and four ferrite inserts positioned as shown in Figure 13. The bobbin coil probe is simulated without a core, and Figure 14 shows good agreement (a deviation of 4.3 % in amplitude and 4.2° in phase) for the clogging signal located at the 545 mm position corresponding to the edge of the plate.

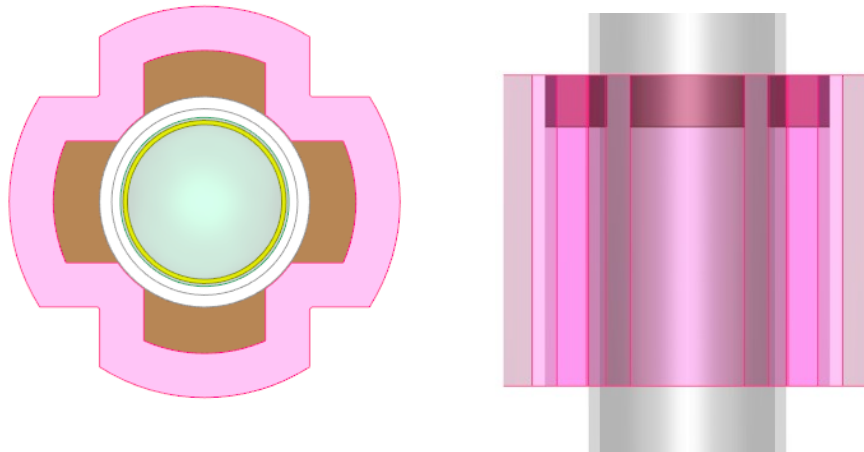


Figure 13. Positioning the clogging in the quadrifoil plate

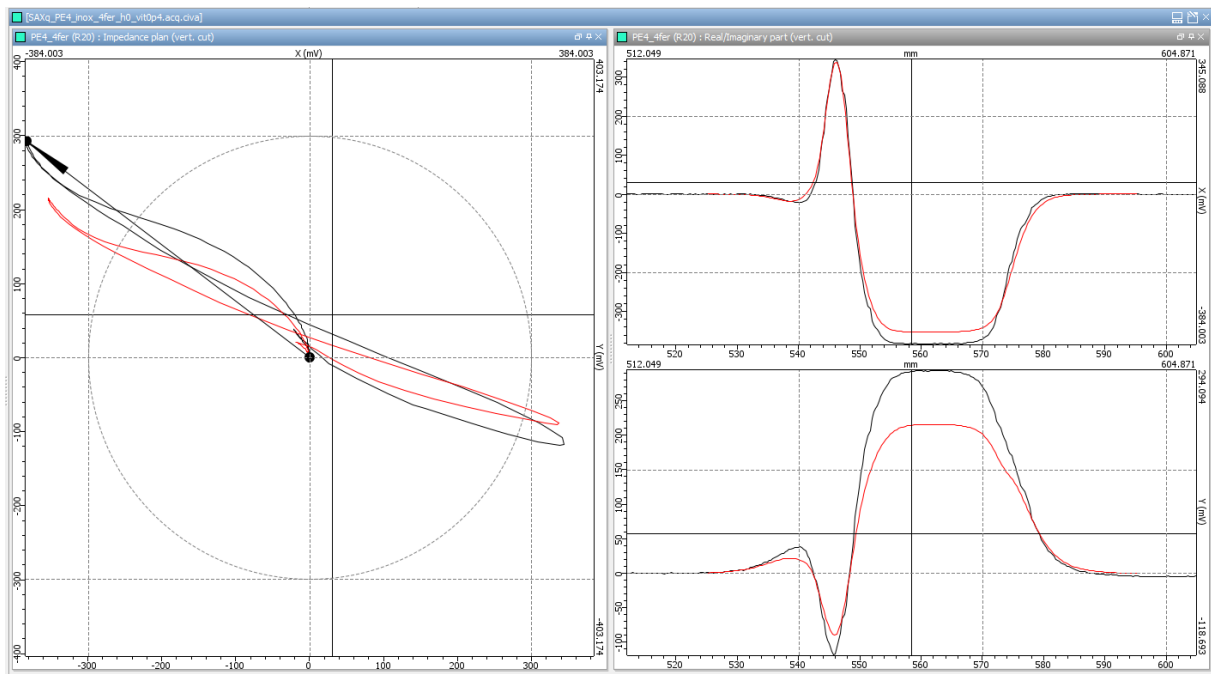


Figure 14: Signal from stainless steel quadrifoil plate with four ferrite inserts, experimental (black) and simulated for a coreless bobbin coil probe (red) excited at 120 kHz.

## 5. Conclusion

The simulation of eddy current inspection of steam generator tubes helps to interpret experimental signals and to demonstrate the performance of the processes used. This is particularly useful for the inspection of the clogging-up of a tube support plate. Full 3D numerical modelling tools are now available in the CIVA simulation platform [9]. They are compared here with experimental data, first on calibration flaws, then in the presence of cylindrical or quadrifoil plates, magnetic or not, and finally with ferrite inserts within the foliation of the non-magnetic quadrifoil plate. The simulated data reproduces the experimental data despite the lack of knowledge of the electromagnetic properties of a core in the axial probe as long as the tube support plate is not magnetic, even in the presence of ferrite inserts. On the other hand, considering an arbitrary description of this sensor core deteriorates the simulated prediction in the presence of a magnetic plate, the electromagnetic properties of which are also

uncertain at this stage. Further validation work is underway, as well as an extension to rotating probes such as the plus-point probe.

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