EDDY CURRENT INSPECTION MODELLING OF THE ELBOW OF A STEAM GENERATOR TUBE WITH THE FINITE ELEMENT SOFTWARE « FLUX® »

Fabrice FOUCHER*, Bastien LAVIE**, Erwan TOUDIC**
* EXTENDE, 86 rue de Paris, 91400 ORSAY, FRANCE
**DCNS, Indret Centre, 44260 LA MONTAGNE, FRANCE

ABSTRACT

Following regulations evolutions, the qualification of steam generator tube bundle inspection by Eddy Current Testing (ET) is now required for French submarines in service inspection. DCNS, one of the world leaders in naval defence and submarines manufacturing, is in charge of these qualification works.
A qualification program has identified a list of influential parameters for this application. This paper deals with one of these parameters: The defect position in the current section of the pin.
DCNS initially planned to evaluate the detection performance by doing extensive tests in these parts. Finally, to reduce the number of experimental tests, only some specific cases supposed to be the worst's were performed: both longitudinal and circumferential external notches, for intrados and extrados, for each bending radius.
To confirm that the chosen cases were the worst, compared to internal notches particularly, EXTENDE and DCNS have conducted a specific modelling campaign. Using the finite elements software FLUX, a quantitative simulation of the eddy current inspection of a pin with a bobbin probe has been computed. The results of this modelling study are detailed in this paper.

CONTEXT

The steam generator is one of the main components of submarines nuclear vessels. It aims at bringing thermal energy from the primary circuit to the secondary circuit. In the framework of a change in the regulations, the qualification of NDT processes for in service inspections of submarine nuclear vessels is required.
One of these inspections consists in the control of steam generator tubes by the Eddy Current technique.

The qualification program has defined the influential parameters to consider for this control. This study has focused on one of this parameter: the position of the flaw in the section of the pin.
Initially, it was planned to test the inspection performance by experimental trials. Due to the numerous cases to consider, (different bending radii, different flaws, OD and ID positioning, etc.) only the worst cases were selected.

In particular, it was decided to consider the longitudinal and circumferential notches located on the outer side as the more critical cases for the detection, compared to the notches on the inner side.
One question is to make sure that this is really the more critical case for the detection after application of the inspection procedure. To confirm the choice to only perform experimental tests on external notches, DCNS has asked EXTENDE to realize a study on this topic. Therefore, a simulation campaign on the defect response obtained by an eddy current bobbin sensor in the elbow of a steam generator tube was conducted with the FEM software package FLUX®.

TECHNICAL OVERVIEW OF THE STUDY

The control of such steam generators (“K15” type) is performed all along the length of the tube. As described above, the current project focused on the elbow of the tube.

The following geometrical configuration was defined for the tubular work piece:

- External diameter: 14 mm
- Thickness: 1.35 mm
- Bending radius: 38 mm

These tubes are made of Incoloy 800, with a conductivity of 1MS/m.

The bobbin probe used is the “A138098B” from ZETEC (figure 1) with an external diameter of 9.8 mm.

Figure 1: Bobbin probe type A138098B from ZETEC

The specifications of the procedure require being able to detect the following reference defects:

- Internal Longitudinal Notch « ILN » (10 x 0.2 x 50%)
- External Longitudinal Notch « ELN » (10 x 0.2 x 50%)
- Internal Circumferential Notch « ICN » (180° x 0.2 x 50%)
- External Circumferential Notch « ECN » (180° x 0.2 x 50%)

In the framework of this study, all of these flaws have been simulated in both the lower surface and the upper surface of the elbow.

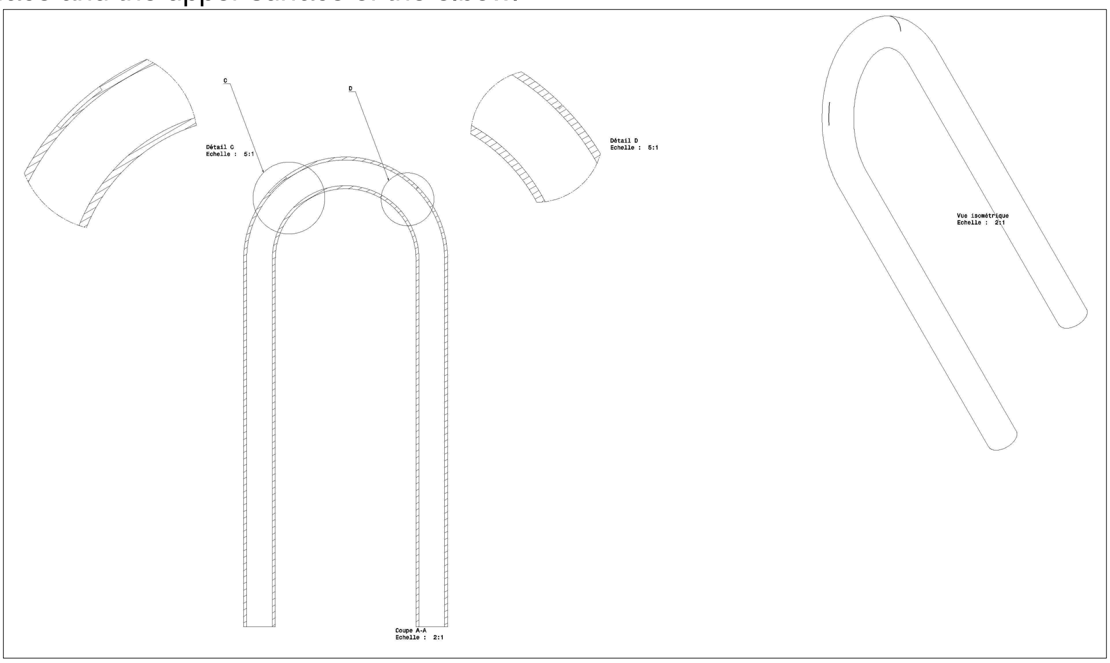


Figure 2: Pin exhibiting a longitudinal and circumferential notch in the upper surface

INSPECTION METHOD

Following the procedure under qualification, the elbow parts of SG tubes are analyzed after applying a combination between 2 differential channels. The combination coefficients are calculated in order to eliminate the signals due to the geometrical transition between the straight part of the tube and the pin.
The two frequencies used in the combination are the following:

- F1 = 170 kHz
- F3 = 35 kHz

Each differential channels F1 & F3 are calibrated before the combination process.
The calibration is done on 3 through wall holes of 0.8 millimetre diameter, separated by 120° in the straight part of the tube under control.
The target signals of the calibration, defined by the procedure, are the following (table 1):

	Amplitude (mV)	**Phase (°)**
Channel F1 (170 kHz)	926	22
Channel F3 (35 kHz)	1566	5

Table 1: Calibration values for F1 & F3 frequencies

After that, the combinated channel “C2” is itself calibrated on the same reference holes in order to reach the following values:

	Amplitude (mV)	**Phase (°)**
Channel C2	1820	0

Table 1: Calibration values for the combinated channel C2

MODELLING IN FLUX SOFTWARE

The simulation has been realized with the FLUX® software, developed by CEDRAT company, in its current commercial release 10.3. FLUX® software is a Finite Element software dedicated to electromagnetics and thermal modelling. This tool is widely used in different applications (electrical machines, magnetic actuators, heat treatment, etc. [1]). FLUX® is also currently used for NDT applications (ET, MT, etc., see for instance [2], [3]). Some works have also been performed using a coupling between FLUX® and the CIVA software, particularly to simulate the inspection of complex parts of SG tubes in nuclear power plants (See for instance [4]).

The FLUX® model used for this study is visualized below (figure 3). The defect (here an internal longitudinal notch located on the upper surface) is represented in red colour and the coils of the bobbin probe are represented in black and pink colours:

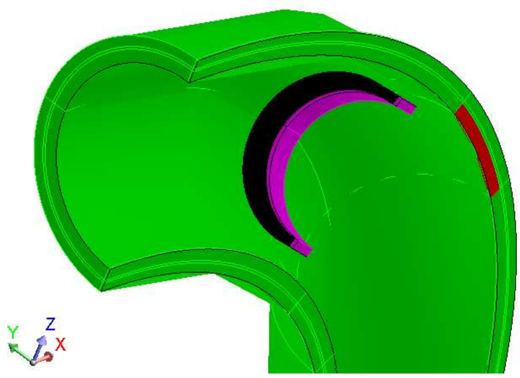


Figure 3: Image of one case simulated in FLUX

The notches being located in the central part of the pin, the represented part of the elbow in the FEM model was limited to an arc of 90°. Moreover, the configuration exhibiting physical symmetries, with respect to the central plane of the tube, only a half of it has been simulated, which helped to reduce the size of the FEM model but accounting for the whole system in the mean time thanks to appropriate boundary conditions.

SIMULATIONS PERFORMED

The full set of notches defined above have been simulated, which means eight total cases, if you consider both the upper and the under surfaces (figure 4).

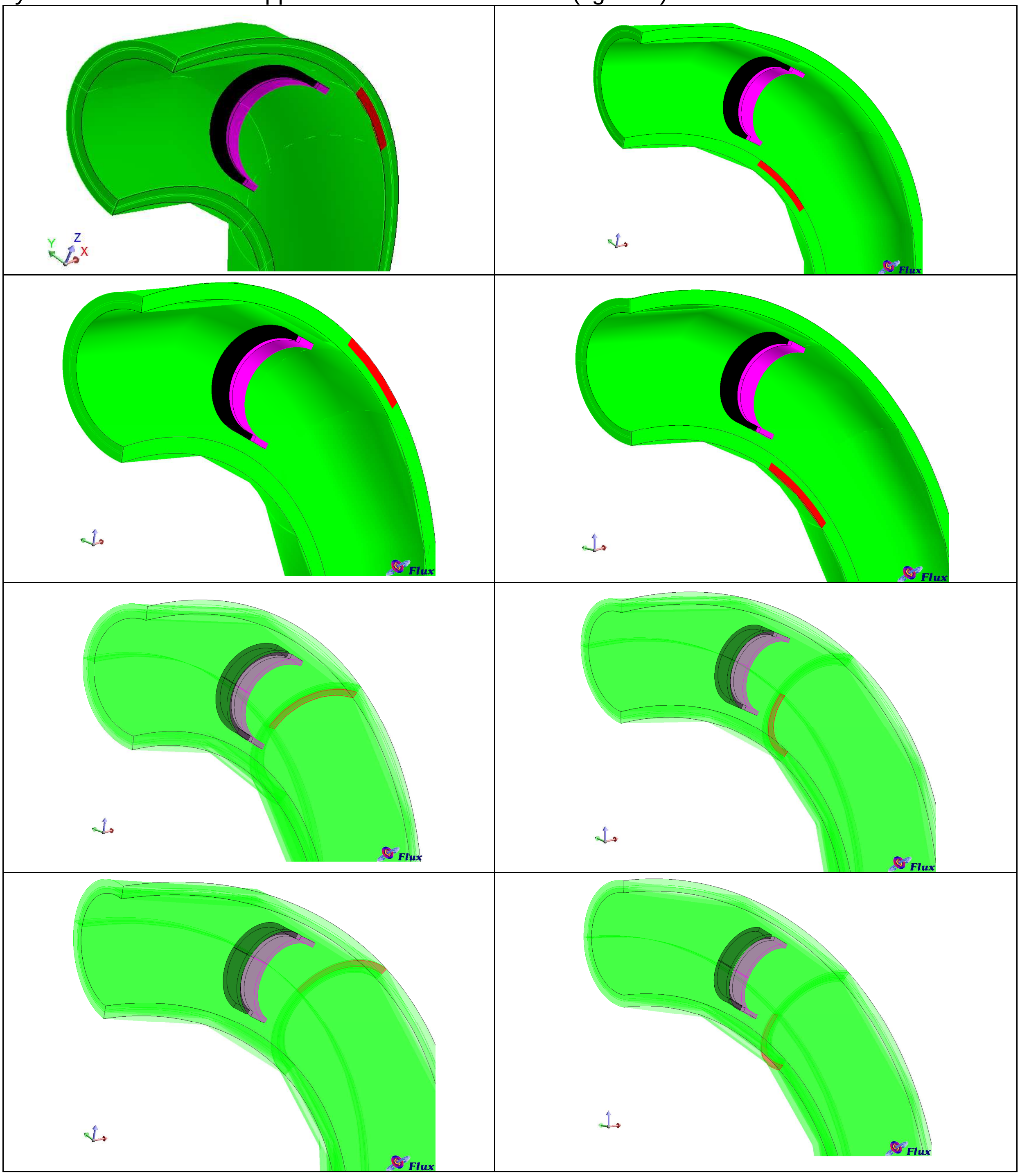


Figure 4: Simulated notches (from top to bottom: Longitudinal internal and external notches, circumferential internal and external notches, on the left: upper surface, on the right: inner surface)

The inspection procedure has been completely simulated. The calibration test described above (3 through wall notches of 0.8mm diameter) has first been computed on FLUX® at both frequencies : 35kHz (channel F3) & 170kHz (channel F1), allowing to find the calibration coefficients (amplification and phase rotation) to apply to the raw signals in order to obtain the target signal defined by the procedure (table1).
Then, after calculation of the 8 defects response, signals are calibrated with these values. Finally, the 2 channels are mixed with the application of a combination matrix [M], allowing to obtain the C2 channel= F1 normalised + [M] * F2 normalised.
The combination coefficients are directly obtained from the analysis software used by DCNS (JADE 1.9.0) for this inspection.
Finally, the channel C2 is also normalized versus the through-wall notches signal (see table 2).
The fact that the whole procedure has been accounted for allowed directly comparing simulation results and measurements available.

RESULTS

The results obtained for the channel C2 on the 4 notches located on the upper surface are shown on the table below:

Defect	Channel	Amplitude (mV)	Phase (degrees)*
ILN- Internal Longitudinal Notch	C2	1931.7	4.1°
ELN- External Longitudinal Notch	C2	1732.0	7.1°
ICN - Internal Circumferential Notch	C2	1264.2	-0.7°
ECN - External Circumferential Notch	C2	1178.0	3.3°

Table 3: Results obtained for the C2 channel on the 4 notches located on the upper surface
**In the measurement convention used here, phase is set to be positive in the clockwise direction*

The curves in the impedance plane are displayed on figure 5. The internal and external notches to be compared are superimposed:

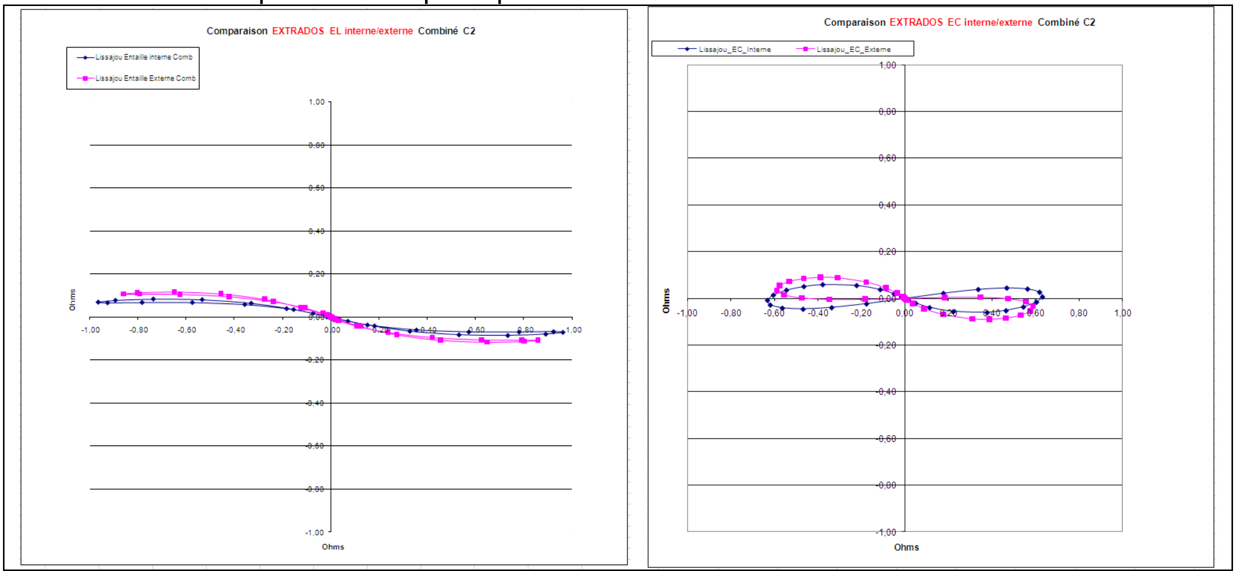


Figure 5 : Signals in the impedance plane in the upper surface: Longitudinal notches (on the left), Circumferential notches (on the right), internal notches (in blue), external notches (in pink)

The same results obtained for the notches located on the inner surface are shown in the table and the figures below:

Defect	Channel	Amplitude (mV)	Phase (degrees)*
ILN- Internal Longitudinal Notch	C2	1749.7	3.9°
ELN- External Longitudinal Notch	C2	1483.2	6.8°
ICN - Internal Circumferential Notch	C2	1349.5	-1.4°
ECN - External Circumferential Notch	C2	1334.3	2.7°

Table 4: Results obtained for the C2 channel on the 4 notches located on the inner surface
**In the measurement convention used here, phase is set to be positive in the clockwise direction*

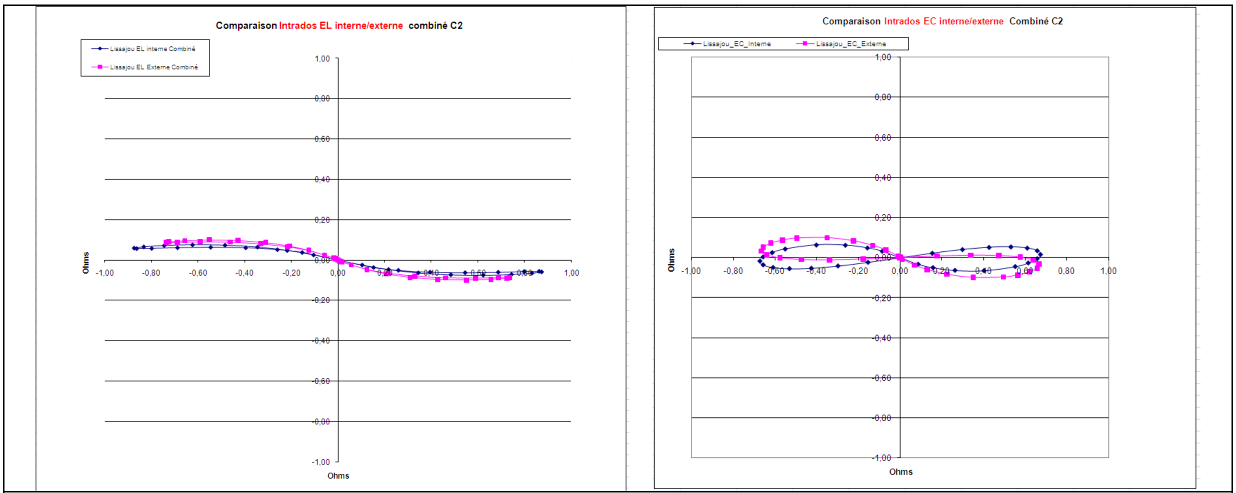


Figure 6 : Signals in the impedance plane in the inner surface: Longitudinal notches (on the left), Circumferential notches (on the right), internal notches (in blue), external notches (in pink)

For each 4 sets of notches, it is always noticed that the signal amplitude obtained on the internal notches is stronger than on the external ones, even if the results are quite close in some cases.
The amplitude difference is expressed below:

- 1% on circumferential notches on the inner surface
- 7% on circumferential notches on the upper surface
- 11% on longitudinal notches on the upper surface
- 18% on longitudinal notches on the inner surface

Thus, whatever the case, this is confirmed that the detection of the external notch corresponds to the most critical case, which confirms the initial hypothesis.

This is also possible to display in FLUX® the eddy current distribution in the pin around the flaw. This capability allows to better understand the disturbance generated by the flaw on the induced currents flowing. You can also visualize the impact of influential parameters such as the materials properties or the frequency, on the penetration depth and the zone coverage by the induced field (figure 7).

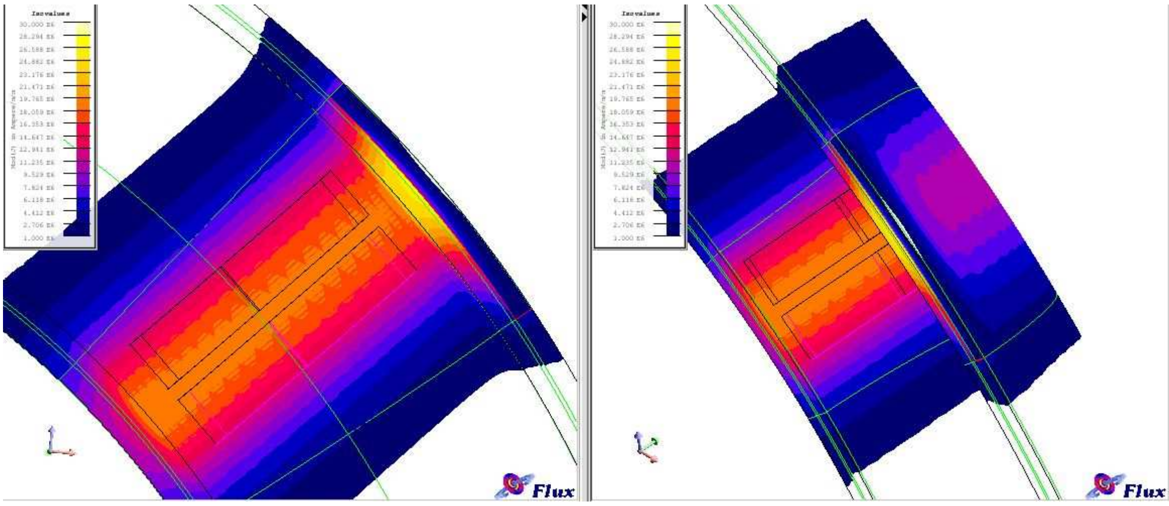


Figure 7: Distribution of eddy currents around the external longitudinal notch located on the upper surface at 170 kHz (threshold of the minimum is 3% of the peak value)

VALIDATIONS

The results obtained in this study have been validated at different steps. First, the impact of the FE mesh has been evaluated in order to ensure that results are stable versus the mesh. Three different meshes have been defined. From a nominal case, a refinement of the mesh has first been done on the elbow part, and then another mesh has been refined on the probe part. This third mesh represents twice more elements than the nominal one.
These three meshes are displayed below (figure 8).

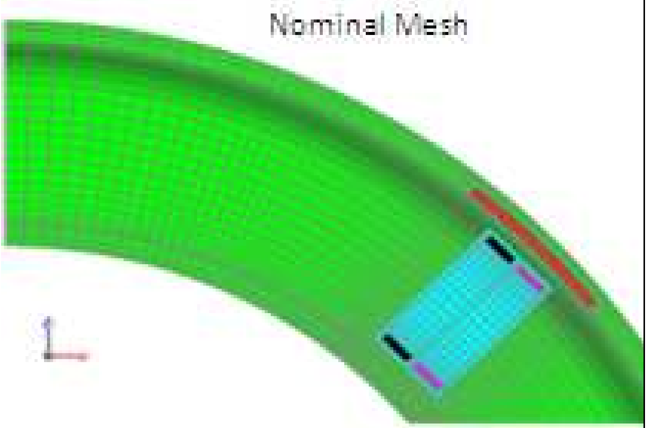
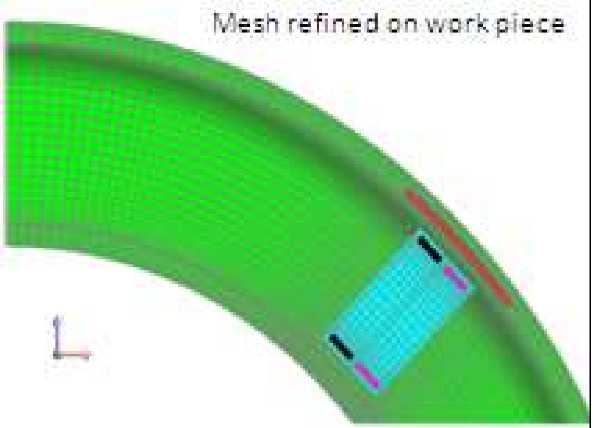
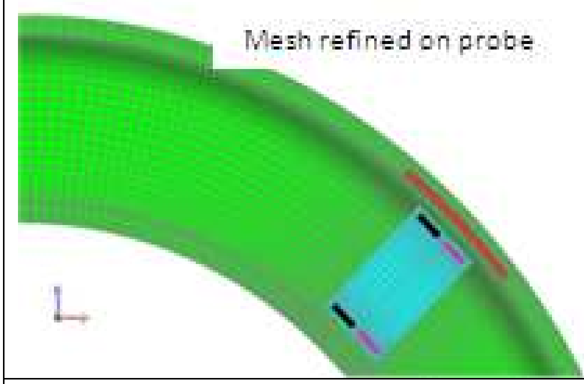
<table>
<tr>
<td>
</td>
<td>
</td>
</tr>
<tr>
<td>Nominal mesh :
338 440 second order elements</td>
<td>Mesh reinforced in the elbow:
564 870 second order elements</td>
</tr>
<tr>
<td>
</td>
<td>
<table>
<tr><th>Mesh</th><th>Variation amplitude</th><th>Phase value</th></tr>
<tr><td>Nominal</td><td>Reference</td><td>92.5°</td></tr>
<tr><td>Refined in the elbow</td><td>-2.99 %</td><td>92.5°</td></tr>
<tr><td>Refined in both elbow & probe</td><td>-2.99 %</td><td>92.5°</td></tr>
</table>
</td>
</tr>
<tr>
<td>Mesh refined on both elbow and probe:
699 790 second order elements</td>
<td>Comparison of the different results</td>
</tr>
</table>

Figure 8: The different meshes tested and the corresponding results

The corresponding results have been compared on the case of the internal longitudinal notch on the upper surface.
The impact of the mesh refinement on the signal amplitude is lower than 3%, and the phase remains constant. This stability reinforces the confidence in the model and as a consequence, we could keep the nominal mesh for the other cases, keeping a reasonable calculation time for the whole study.

Then, a comparison between the model and measurements has been done on both longitudinal external and internal notches on the upper surface. The comparison exhibits a very good agreement between simulation and experiments with less than 4% difference in the amplitude and less than 1° difference in the phase of the signal (table 5).

	Simulation	Experiment	Difference
Amplitude Internal LN	1931.7mV	1912mV	1%
Phase Internal LN	4.1°	5°	0.9°
Amplitude External LN	1732mV	1656mV	4%
Phase External LN	7.1°	7°	0.1°

Table 5: Comparison Simulation & measurement with longitudinal notches on the upper surface

CONCLUSION

In the framework of changes in the regulations, the qualification of the Eddy Current Inspection of steam generator embedded in submarines nuclear vessels is required.
The position of the flaw in the pin of the SG tube is defined as an influential parameter in the qualification program.
To study this parameter, an experimental campaign was defined with external longitudinal and circumferential notches. But, the question is to know if the outer position is really the worst case for the detection with the existing inspection procedure.
The simulation study performed on the FLUX software allowed to confirm this hypothesis and then it confirms the choice that has been made to focus the experimental tests on mock-ups with external notches only.

References

[1] http://www.cedrat.com/en/software-solutions/flux.html
[2] « Simulation of ET NDT with FLUX & CIVA », F. Foucher, X. Brunotte, A. Kalai, Y.Lefloch, G. Pichenot, D. Prémel, COFREND conference, Beaune 2005
[3] « Cofrend working group on ECT NDE simulation-review of activities », M. Mayos, M. Lambert, C. Gilles-Pascaud, M. Dessendre, N. Dominguez, F. Foucher, Ali Abakar, journées COFREND, Toulouse 2008
[4] « A hybrid volume integral-finite elements approach for the simulation of eddy current inspection of steam generator tubes in the region of quadrifoiled support plate », A. Skarlatos, C. Gilles-Pascaud, G. Pichenot, G. Cattiaux, T. Sollier, QNDE 2009