E.C. Inspection modeling of the elbow of a steam generator tube with Flux®.

F. Foucher - EXTENDE ; B. Lavie ; E. Toudic - *DCNS*.

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. This study has focused on one influential parameter of the control: 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. To confirm this choice allowing to only performing 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: External diameter: 14 mm; Thickness: 1.35 mm, Bending radius: 38 mm) is performed all along the length of the tube. As described above, the current project focused on the elbow of the tube. These tubes are made of Incoloy 800, with a conductivity of 1MS/m. The Eddy Current bobbin probe used for this inspection has an external diameter of 9.8 mm.

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.

Modeling in Flux software

The simulation has been realized with the Flux® software, developed by CEDRAT company, in its current commercial release 10.3. 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. The Flux® model used for this study is visualized below (figure 1). The defect is represented in red colour and the coils of the bobbin probe are represented in black and pink colours. The full sets of notches defined above have been simulated, which means eight total cases, if you consider both the upper and the inner surfaces (on figure 1, only defects located on the upper surface are represented):

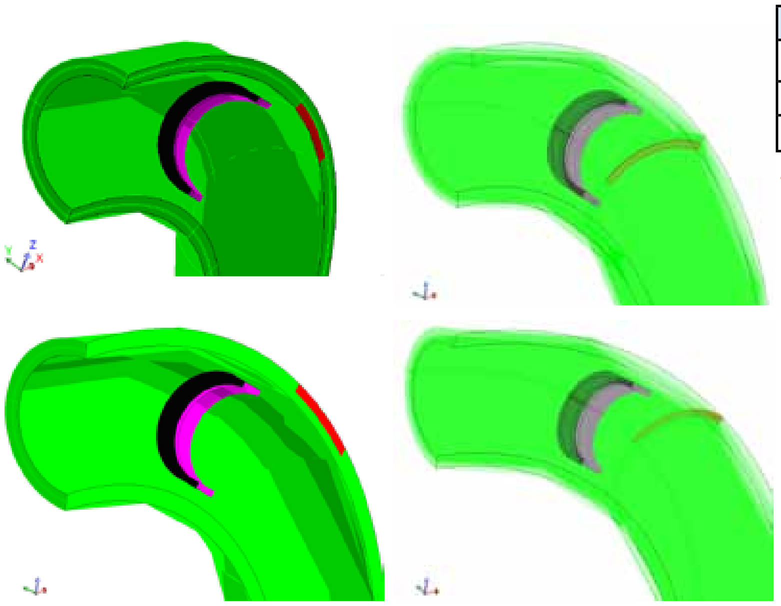

Fig. 1: Simulated notches (from top to bottom: Internal and external notches, on the left: longitudinal flaws, on the right: circumferential notches).

Inspection method

Two differential channels F1 & F3 are defined in the inspection procedure using two different frequencies: F1 = 170 kHz and F3 = 35 kHz

Then, the calibration of each differential channel 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 mentioned in the table 1.

After that, a combination matrix [M] is applied between the 2 differential channels allowing to obtain the C2 channel = F1 normalised + [M] * F2 normalised. The four complex combination coefficients of [M] are calculated in order to eliminate the signals due to the geometrical transition between the straight part of the tube and the pin. Finally, the combinated channel "C2" is itself calibrated in order to reach the following values for the same reference holes:

	Amplitude (mV)	**Phase (°)**
Channel F1 (170 kHz)	926	22
Channel F3 (170 kHz)	1566	5
Channel C2	1820	0

Table 1: Calibration values for F1 & F3 frequencies and for the combinated channel C2.

(see continued on page 11)

Defect	Channel	Amplitude (mV)	Phase (°)*
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 2: Results obtained for the C2 channel on the four notches located on the upper surface. * In the measurement convention used here, phase is set to be positive in the clockwise direction.*

This inspection procedure has been completely simulated in Flux which allows 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 2.

The curves in the impedance plane are displayed on figure 2. The internal and external notches to be compared are superimposed.

The same type results have been generated for the notches located on the inner surface.

For each four 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% higher amplitude for internal circumferential notches compared to external 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

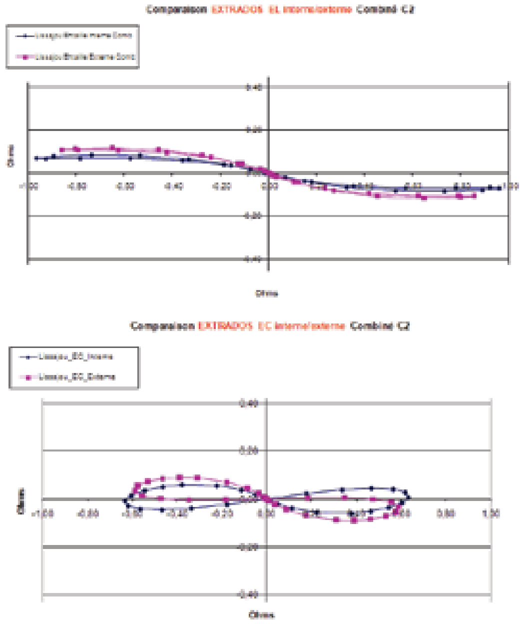

Fig. 2 : Signals in the impedance plane in the upper surface: Longitudinal notches (on the left), Circumferential notches (on the right), internal notches (in blue), external notches (in pink).

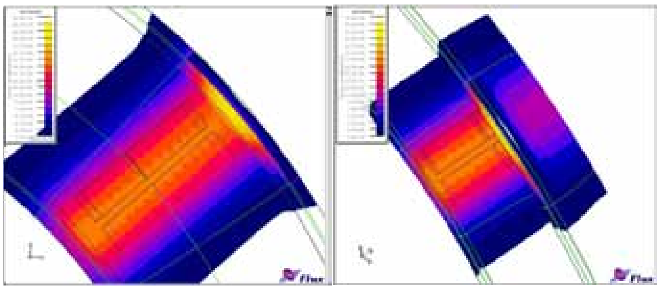

Fig. 3: Distribution of eddy currents around the external longitudinal notch located on the upper surface at 170 kHz (threshold of the minimum is 3% of the peak value).

This is also possible to display in Flux® the Eddy currents 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 3).

Validation

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 3).

	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 3: Calibration values for the combinated channel C2.

Conclusion

Whatever the case, the simulation study confirmed that the detection of the external notch corresponds to the most critical case. This result confirms the initial hypothesis of DCNS, allowing to reduce the number of mock-up tests to perform for the qualification works.